A STUDY OF THE FEASIBILITY OF UNDERGROUND COAL GASIFICATION IN THE BOWRON AND TULAMEEN COALFIELDS OF BRITISH COLUMBIA

(PART OF THE COST SHARED CANADIAN COAL CONVERSION PROGRAM)

Final Report

by

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NOMENCLATURE

daf basis	- value based on dry and ash-free sample weight, sometimes abbreviated as "daf"
dry basis	- value based on dry sample weight, sometimes abbreviated as "dry"
FSI	- free swelling index
kmol	- kilomol
kPa	- kilopascal; unit of pressure
m	- meter
mD	- milliDarcy; unit of permeability
MJ	- megajoule of energy
mol	- the amount of substance containing the same number of atoms as 12 g of pure carbon-12
Mt	- million metric tonnes
OD	- outside diameter
vol %	- concentration as percentage on a volume basis
wt %	- concentration as percentage on a weight basis

I. SUMMARY

A. GEOLOGICAL CHARACTERISTICS OF THE BOWRON AND TULAMEEN COALFIELDS

The Bowron and Tulameen coalfields were considered in this study as a result of findings from a previous survey of the suitability of most coals in British Columbia for underground gasification.

The Bowron coalfield is located approximately 55 km east of Prince George in the Bowron River Valley. The Bowron River meanders over the coal basin, which measures about 2 km in width and 19 km in length. Norco resources holds coal licenses for the coalfield and is proposing to mine some 20 Mt of thermal coal by underground mining methods. No final plans for development of the mine are known to exist.

The Bowron basin is a synclinal sedimentary basin trending northwest-southwest. Three coal seams are present in the central portion of the basin, one of which (Main seam) is of sufficient thickness and continuity for underground gasification. This seam contains some 50.6 Mt of swelling bituminous coal in a coal zone having a total thickness of 5.25 m. The other two seams are less well defined, but may contain another 8.3 Mt. The dip of the Main seam decreases from 45° at surface to near 30° at depths of 300 to 600 m.

The Tulameen coalfield is located about 15 km west of Princeton and within 3 to 4 km of the small communities of Tulameen and Coalmont. The coalfield has moderate relief. No rivers are present over the coalfield, and creeks are sparse.

Cyprus Anvil Mining Corporation holds coal licenses for the coalfield and has proposed a surface mining operation for the west side of the basin. Development of this mine is dependent on obtaining a sales contract and an increase in the price of thermal coal.

The coalfield is a dish-shaped, sedimentary basin oriented in a northwest-southeast direction. Coal outcrops on the periphery of the basin and increases in depth to in excess of 600 m at its center. Two seams are of substantial thickness: Main seam--17.5 m; Lower seam--3.5 m. Only the Main seam was considered for recovery by underground gasification. A total of some 225 Mt of bituminous coal is present in the Main seam with a further 45 Mt potentially present in the Lower seam. Of the total in the Main seam, 78 Mt is present at a depth of less than 600 m and a dip of greater than 30°.

B. UNDERGROUND COAL GASIFICATION PROCESSES

The two main processes being developed are the Steeply Dipping Bed process and the Linked Vertical Well process. Linked Vertical

Wells are used in seams having a dip of less than about 30°. The Steeply Dipping Bed process is used in seams dipping at greater than 30°, and utilizes an inclined production borehole drilled along the seam from surface and vertical or inclined intersecting injection wells. For this process, gasification proceeds in the up-dip direction consuming the uncased production borehole.

Both processes have been used in small Soviet production plants. Field trials of both processes have been made in the United States and Canada, mostly in subbituminous coals which shrink and fracture when heated. Bituminous coals tend to swell when heated and, for this reason, are more difficult to gasify.

Gasification with air yields a fuel gas containing 50 to 55 vol % nitrogen and having a heating value of 4.5 to 5.7 MJ/m^3. The heating value increases to 9 to 11 MJ/m^3 when gasification is conducted with oxygen and steam.

Low heating value gas may be used for direct combustion such as for steam raising and electricity generation. Medium heating value gas obtained by oxygen gasification may be used as a feedstock for synthesis gas or synthetic natural gas.

The main potential environmental impacts of the process are surface and subsurface subsidence and disturbance of regional groundwater quality and flow. Field trials to date, although of short duration, have shown that coal surrounding the gasifier adsorbs most potential groundwater contaminants, reducing the migration of contaminants with groundwater.

C. SUITABILITY OF THE COALFIELDS FOR UNDERGROUND GASIFICATION

A previously developed numerical procedure was used as a first-stage evaluation of the suitability of the Main seams of both coalfields for gasification. The weighted average ratings of the seams were 52 for the Bowron coalfield and 44 for the Tulameen coalfield. These ratings are out of 78, indicating both seams are suitable for gasification.

Consideration of factors not incorporated into the numerical procedure erodes some of the suitability of the Bowron coalfield. A major negative aspect of this coalfield is the presence of the Bowron River.

The suitability of the Tulameen coalfield is believed to be higher than indicated by the rating procedure due to the large resource and the small areal extent of the coalfield. Further study of the potential for contamination of potable water wells by a gasification plant in the Tulameen coalfield is needed. In this study, it was assumed that contaminant migration would not pose a problem.

D. SYNTHETIC NATURAL GAS AND SYNTHESIS GAS PLANTS

Synthetic natural gas (SNG) and synthesis gas (syngas) were considered in this study. The nominal output capacities of the plants are:

SNG: 1.5×10^6 m^3/d (53×10^6 scf/d)

Syngas: 3.8×10^6 m^3/d (134×10^6 scf/d)

The same coal consumption rate applies to the SNG and syngas plants. The output capacities were chosen such that all the reserve in the Bowron coalfield would be consumed over a 20-year operating life. Consequently, only 23% of the reserves present in the Tulameen coalfield would ultimately be consumed.

The coal consumed by the plants is 2.60 to 2.69 dryMt/yr for the two coalfields. On average, this amounts to 53 Mt over a 20-year plant life. Actual consumption is about 90% of this for the conditions used for the base case.

Capital investment and operating costs were determined for the Bowron and Tulameen coalfields. The same surface facility was used for each case, therefore, capital costs differed only as a result of different drilling requirements. These costs were estimated in mid-1982 dollars, then were inflated to January 1983 at a rate of 3.5% for use in the financial model. Costs are as follows:

		Total Capital Investment (Jan.1983 $ X 10^6)	Operating Cost (Jan.1983 $ X 10^6)	
			Constant	Proportional
Bowron Coalfield	SNG	344.925	22.208	24.512/14.558[a]
	Syngas	305.631	19.914	23.056/13.102
Tulameen Coalfield	SNG	333.683	21.979	9.672/9.350/5.425[b]
	Syngas	294.389	19.685	8.216/7.894/3.969

[a] First through nineteenth operating year/twentieth operating year.

[b] First operating year/second through nineteenth operating year/ twentieth operating year.

E. FINANCIAL ANALYSIS

Product prices for SNG and Syngas were determined for a set of base case conditions. The sensitivity of these prices to cost estimates and economic factors was subsequently investigated.

The project was assumed to be funded by 100% debt at an interest rate of 11%. All revenue, capital costs, and operating costs were assumed to inflate at a constant rate of 7% per year.

The plant was assumed to begin production in 1986 after a 3year construction period.

Base case product prices were as follows.

Product	Plant Location	Product Price Jan.1983 $/GJ	Product Price Jan.1983 $/10^{3}m^3
SNG	Bowron Coalfield	4.19	152.10
	Tulameen Coalfield	3.37	122.33
Syngas	Bowron Coalfield	3.58	54.06
	Tulameen Coalfield	2.81	42.43

The sensitivity analysis demonstrated that a 50% increase in the purchase price of the land and coal rights, or a 20% increase in the inflation rate had a very small effect on product price. The highest product prices resulted from the assumption of zero inflation and an 11% interest rate on debt. In this case, the cost of SNG and syngas for the Tulameen coalfield rose to $5.06/GJ and $4.22/GJ, respectively.

F. CONCLUSIONS AND RECOMMENDATIONS

1. Considering both the technical suitability of the Bowron and Tulameen coalfields and the product prices predicted by the financial analysis, the Tulameen coalfield is the most attractive site for underground coal gasification. The positive features of this coalfield are discussed in detail in Chapter XI.

2. The highest product prices determined from the sensitivity analysis resulted from an assumption of a zero inflation rate at an interest rate on debt of 11%. This is believed to be an upper bound on product prices.

3. Considering the proximity of the Inland Natural Gas pipeline to the Tulameen coalfield, SNG is the preferred product.

   Syngas would have to be transported to a user in a dedicated line. A potential industrial user of this product for synthesis of chemical products does not exist nearby.

4. Based on the identified reserve for the Tulameen coalfield, nominal plant capacities of up to 6.5 X 10^6 m^3/d SNG or

16.4 X 10^6 m^3/d syngas could be supported. SNG and syngas prices would decrease from the predicted values with increasing plant sizes due to economics of scale.

5. To build a prototype underground coal gasification plant at the Tulameen coalfield, a 6- to 10-year program of process modeling, laboratory experimentation, and field trials is required. A major portion of the work in areas of process modeling and laboratory experimentation should precede any field trials.

   The budget cost for site characterization and a series of four field trials of increasing scale is $10,500,000. This cost does not include any major complimentary studies and laboratory experimentation that may be needed while the field trials are being undertaken. The budget costs of a detailed geological and hydrogeological study is $500,000.

6. The following list identifies some of the initial work that would have to be undertaken if underground coal gasification is to be applied in the Tulameen coalfield; a more thorough discussion of the developmental work that would be needed is given in Chapter X.

   a) A study should be undertaken to refine the estimate of product gas yield and quality using computer process models available at, for example, the Laramie Energy Technology Centre. To conduct this work, the composition of coal samples from the coalfield would have to be determined.

   b) An inspection of the coalfield should be made to map the topography and surficial geology of the area and obtain data which is needed for siting and designing the gasification and plant areas.

   c) A study of the environmental impact of the process should be conducted using data from pilot tests conducted elsewhere. These data would identify the type and yield of contaminants, effects of subsidence, extent of groundwater contamination, and effect of the process on regional groundwater flow, amoung other factors.

   d) To ascertain whether there would be unacceptable contamination of groundwater flows and a hazard to downstream users of this water and to supply data for possible field testing, a hydrogeological study should be undertaken. This study would require the drilling of several wells, coring of the formation to define rock types, and computer modeling of groundwater flows. Data obtained in c) above would be used in this study as input data and to confirm predictions of contaminant migration.

II. INTRODUCTION

A. BACKGROUND

Underground coal gasification (UCG) enables recovery of the energy content of coals either as low-heating-value gas with injection of air, or as medium-heating-value gas with injection of a steam-oxygen mixture. This process is aimed at recovery of coals not suited for technical or economic reasons to conventional surface or underground recovery techniques. Because of the vast coal resources in the United States, Canada, West Germany, Soviet Union, Belgium, and other countries which are not suitable for conventional recovery, there have been numerous efforts in these countries to further development of UCG technology. Significant field testing of the technology in horizontal lignite, in horizontal and dipping subbituminous coals, and horizontal bituminous coals has been undertaken to various extents in the United States since 1972. In Canada, the Alberta Research Council conducted a field test in a subbituminous coal seam near Forestburg, Alberta, in 1976.

The results from field tests conducted in the United States have led to considerable optimism for the commercial potential of UCG. Many economic studies have indicated that the cost of energy produced using UCG is comparable to, or less than, the cost of energy production by competing technologies. Granted the present uncertainty of the production cost of fuel gas using UCG, the various cost estimates reasonably indicate the potential economic benefit of the technology.

A study of the suitability of British Columbia and Nova Scotia resources for underground gasification (Edwards, 1981) concluded that for the two most-developed underground coal gasification processes, Linked Vertical Well and Steeply Dipping Bed, a chemical conversion efficiency of near 76% and a coal recovery efficiency of about 70% could generally be achieved. These lead to an energy recovery efficiency (higher heating value of clean gas/higher heating value of coal contained between process wells) of about 53%. This recovery efficiency is at the higher end of the range of what may be achieved by underground room and pillar methods, and is modestly below the recovery efficiency of longwall mining methods.

The produced fuel gas has a heating value of 3.7 to 5.7 MJ/m^3 with air injection and 9.3 to 11 MJ/m^3 with injection of a mixture of oxygen and steam. These ranges are essentially identical to those for surface gasification of mined coal.

A previous study by B.H. Levelton & Associates Ltd. (Edwards and Vogwill, 1981) concluded that the Bowron coalfield is the most suitable coal deposit in British Columbia for underground

gasification. Using a comprehensive set of suitability criteria, the lower seam of this deposit was assessed a suitability rating of 58 out of a possible 78, indicating fair to good suitability for gasification. This rating was the highest of all seams investigated in the study of coalfields in British Columbia and Nova Scotia. At the time of this study, the identified resource in the Bowron coalfield was 59 million tonnes.

The seams of the Tulameen coalfield achieved suitability ratings of 30 and 46, indicating fair suitability for underground gasification. The coal in these two seams is of high volatile C bituminous rank and has a low swelling index (FSI = 1 to 2). The resources present in the main seam of this coalfield is 225 million tonnes.

As a consequence of the fair to good suitability ratings of the Bowron and Tulameen coalfields for underground gasification, they were selected for the more-detailed process and economic analysis contained in this report.

B. SCOPE OF WORK

The scope of work as outlined in the Terms of Reference are as follows:

Task 1 - Regional Evaluation

a) Regional evaluation of the coalfields will be performed by Dolmage, Campbell & Associates Ltd. as follows:

- Map out approximate areas of seams meeting or exceeding critical suitability criteria,

  2 m coal thickness
  100 m depth
  Dips 15°; 35° to 75°; and others.

- Compile additional characteristic data for the coalfield of the type presented in the 1981 Dolmage Campbell report. These data comprise geological, coal quality, seam quality, location, and geographical information. Qualify the accessibility of the coalfield.

- Determine ownership of coal rights and present information on past and planned mining activities.

Task 2 - Product Routes and Cost Estimates

a) Survey the literature for previous economic analyses.

b) Determine possible product routes and production cost estimates for these products. Estimate the heating value of the product gas and tars from underground gasification.

c) Recommend the most attractive scenario for product route and end use. Possible use of the product gas from underground gasification will be electricity generation, industrial heating, pipeline gas, methanol synthesis.

Task 3 - Environmental Evaluation

Provide an outline of the environmental effects and potential problems arising from underground gasification in the areas of the Bowron River and Tulameen coalfield.

Task 4 - Development Scheme

Formulate an outline for development of underground gasification in the Bowron River and Tulameen coalfields. This outline will identify the future studies, laboratory experimentation, and field testing that is needed to commercialize the process. Make recommendations on the technology to be used based on performance of tested technologies.

In conducting the analysis for product routes and costs of these products, emphasis was placed on gaseous products of commerce, not liquid fuels or electricity. This was done since production of these gaseous products by underground gasification are of most interest to the B.C. Hydro Gas Group at the present time.

III. GEOLOGICAL CHARACTERISTICS OF THE BOWRON AND TULAMEEN COALFIELDS

Geological characteristics of the Bowron and Tulameen coalfields were compiled in a previous report by Dolmage Campbell & Associates Ltd. entitled "Potential Coal Sources in British Columbia" (March, 1981). These data were used to evaluate the suitability of most coal seams in British Columbia for underground gasification as part of a study for Energy, Mines, and Resources Canada (Edwards and Vogwill, 1981).

Dolmage Campbell & Associates Ltd. undertook to update and obtain more detail on the geological characteristics of the Bowron and Tulameen coalfields relevant to underground coal gasification. In the previous work, characteristics were assembled that were felt to best reflect the general nature of the coalfields, and that would be sufficiently representative as to allow an assessment of the suitability of the coalfield as a whole for underground gasification. Because these data were very generalized, more study was conducted for this work to obtain a more detailed definition of geological features within the coalfield and improve the estimate for the coal resource.

The following parameters (Table 1) were used to define the resources of the Bowron and Tulameen coalfields potentially suitable for underground gasification. These parameters are based on findings from Phase I of the study by B.H. Levelton & Associates Ltd. (Edwards, 1981) with the exception of the distances laterally and down-dip of old or proposed mine workings. The 100-m value was chosen as a very approximate estimate, and is based on the experience of developers with gas leakage from experimental field gasifiers.

In the following sections on the Bowron and Tulameen coalfields, only a brief discussion of geological characteristics is given. The complete report by Dolmage Campbell & Associates Ltd. on these coalfields is contained in Appendix A "Geological Characteristics of the Bowron and Tulameen Coalfields With Respect to Underground Gasification".

A. BOWRON COALFIELD

1. Location and Physiography

The location of the Bowron coalfield and its proximity to existing gas pipelines are illustrated in Figure 1. The Bowron basin is located approximately 55 kilometers east of Prince George in the Bowron River valley and south of Provincial Highway No. 16.

The Bowron River meanders over the full length of the Bowron basin in a flat-bottomed valley having a width of 2 to 3 kilometers and an elevation of 750 m above sea level.

Table 1

PARAMETERS USED TO DEFINE THE RESOURCES OF THE COALFIELDS

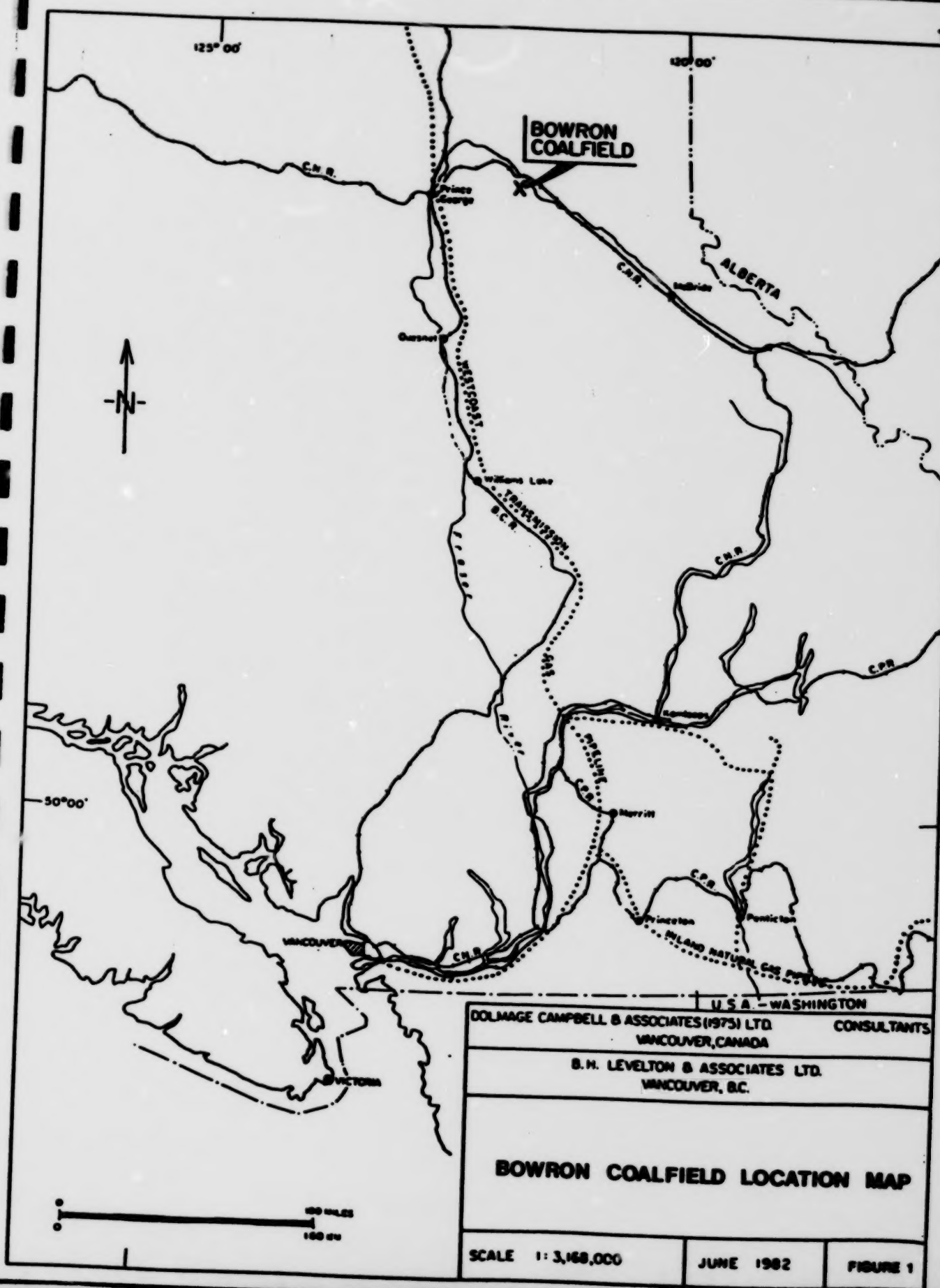
1. Minimum seam thickness considered is 1 metre.

2. Minimum workable seam depth is 100 metres; resources are estimated for depth increments of 100 to 300 metres, 300 to 600 metres, and greater than 600 metres.

3. No resources are included within 100 metres laterally or down-dip of old or proposed mine workings.

4. Severely crushed areas in coal zones are excluded where they may result in channelling to mine workings or to surface.

5. Total ash content (inherent ash in the coal plus rock partings) up to approximately 50 percent is acceptable.



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VANCOUVER, CANADA

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VANCOUVER, B.C.

BOWRON COALFIELD LOCATION MAP

SCALE 1: 3,168,000 | JUNE 1982 | FIGURE 1

Valley walls rise to summits of about 1,220 m. Overburden consisting of glacial fill and river gravels is in the order of 30 m thick.

The Bowron basin is elongated in shape, having a width of about 2 km and a length of 19 km by present estimates. Surface uses comprise logging and cattle grazing. In the coalfield area, there is no habitation other than temporary camps.

2. Property and Ownership

The coal basin, as well as possible extensions to the north and south, are covered by 51 coal licenses held by Norco Resources Ltd. of Vancouver, British Columbia. The licenses encompass an aggregate area in the order of 12,000 hectares. The main portion of the coal basin, as defined by rock exposures, drill holes, and magnetic surveys, is approximately 3,500 hectares in area.

Norco Resources Ltd. holds the following licenses:

CL 148
CL 162 - 163
CL 4458 - 4464
CL 4723 - 4727
CL 6043 - 6044
CL 6343
CL 6540 - 6572

3. Proposed Mining

Norco Resources is proposing to mine some 20 million tonnes of thermal coal by underground methods, although the specific areas to be mined and the mining plans have not been finalized. However, the general area in which mining will be done is approximately the same as the reserve areas shown in Figure 2. Areas outside the identified reserve areas may contain coal, but exploration data in these areas are nonexistant or too sparse to confirm such possibilities at this time.

4. Geological Setting

The Bowron basin, as determined from surface and subsurface geology and from aeromagnetics, consists of a long, narrow, northwesterly-striking sedimentary basin that is covered by glacial till and river gravels. It is synclinal in cross-section and may be bounded by a fault along part of its northeast side. At least one transverse fault has been indicated from drilling results within the central portion of the basin.

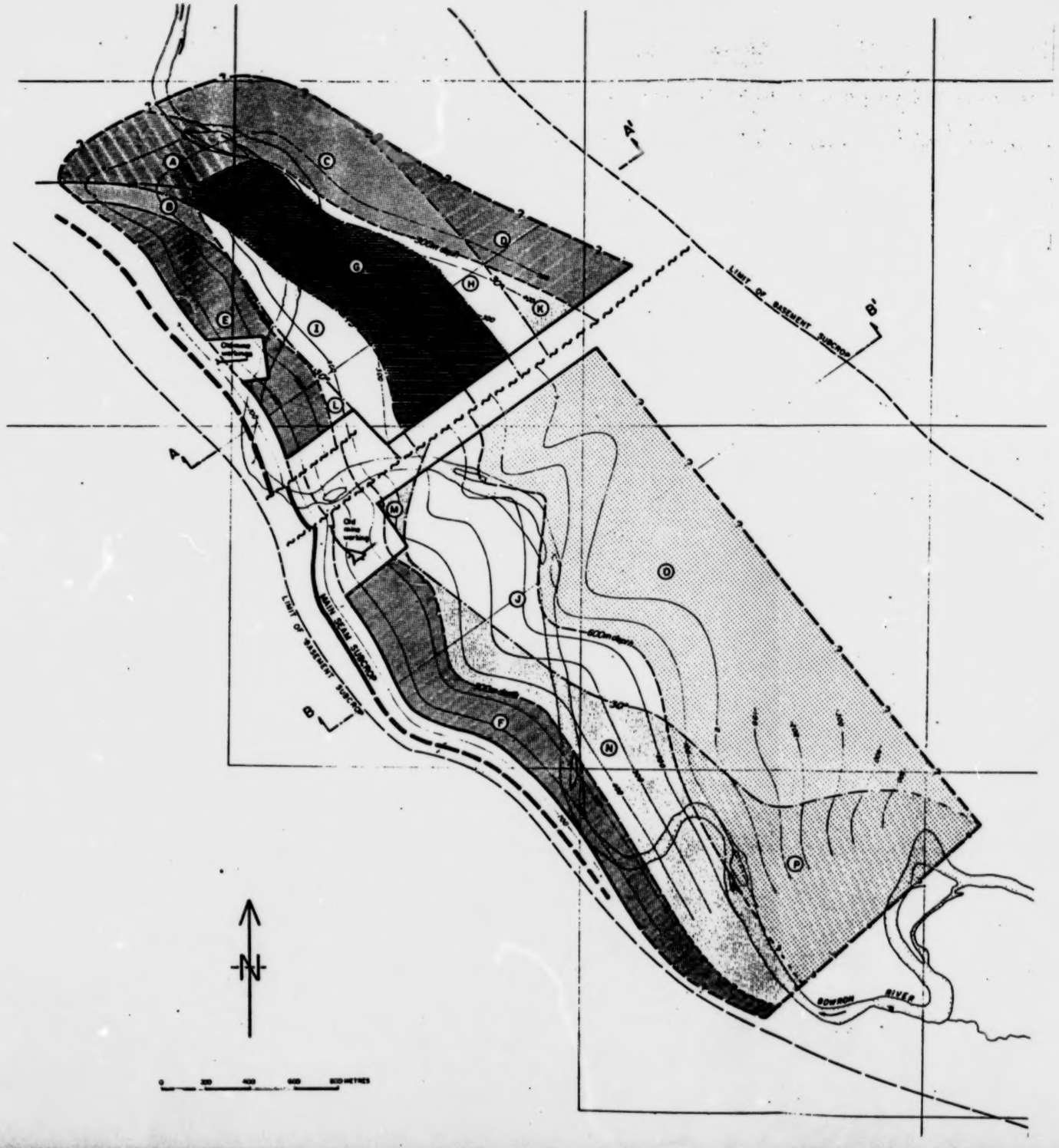


FIGURE 2 BOWRON COALFIELD RESERVE AREA

The explored portion of the basin, the central 25%, comprises the Bowron coalfield.

5. Coal Occurrences

The Bowron coalfield contains three coal seams of interest for this study (Figure 3). Other seams exist, but are of little consequence. The Lower or "Main seam" is the most continuous and the thickest seam. The two overlying seams, the Middle and Upper seams, are reasonably continuous only in the shallower, northwestern part of the coalfield. Norco Resources proposes mining of the Main seam only.

Shale of variable thickness borders the top and bottom of the Main seam. Within the seam is clean coal, high-ash coal, coaly siltstone, and mudstone partings. Partings and high-ash coal occupy approximately 15% of the seam thickness.

The Middle and Upper seams are also encased in shale and sandy shale, and both probably have a composition that is similar to the Main seam. Insufficient data are available to define the quality of these two seams at the present time.

The Main seam has been analyzed sufficiently to provide reliable quality data. The characteristics of interest for underground gasification of this seam are summarized in Table 2. The higher heating value of cleaned coal (approximately 9 wt% ash) is 28.7 MJ/kg.

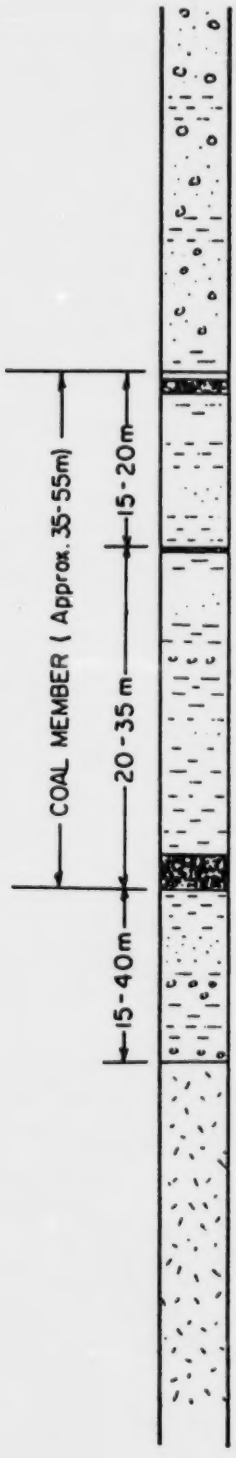
For the present, the quality of the Upper and Middle seams may be assumed to be similar to the Main seam.

6. Coal Reserves

Total seam reserves were calculated for the Main seam throughout the presently-identified coalfield. The reserves present in the Upper and Middle seams were estimated for the northwestern part of the coalfield only.

The reserves were estimated by using data measured in the southwest part of the coalfield and extrapolating this data to the northeast part of the field. The following average seam thicknesses were used: Main seam - 5.25 m; Middle seam - 1.65 m; Upper seam - 1.2 m. Aggregate cleaned-coal thickness would be, respectively, 4.45 m, 1.4 m, and 1.0 m.

Parts of the coalfield having depths of overburden of 100 to 300 m, 300 to 600 m, and greater than 600 m, and seam-dips of 0° to 15°, 15° to 30°, and greater than 30° are estimated in Figure 4. These data were used for the evaluation of the suitability of the Main seam for underground gasification.



Predominantly conglomerate, sandstone, siltstone and minor shale

Upper seam (1.2 m av.)

Middle seam (1.65m av.)

Shale with some siltstone and minor sandstone and conglomerate; some carbonaceous shale and thin coal seams.

Main seam (5.25m av.)

Unconformity

Basement units (predominantly volcanic rocks)

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BOWRON COALFIELD

STRATIGRAPHIC SECTION OF THE COAL MEMBER

SCALE : VERT. 1:1000	JUNE 1982	FIGURE 3

Table 2

COAL CHARACTERISTICS FOR THE MAIN SEAM OF THE BOWRON COALFIELD

	As-Received Basis (wt%)	Dry Basis (wt%)	Dry, Ash-Free Basis (wt%)
Coal Composition:			
Moisture	4.4		
Volatile Matter	32.9	34.4	44.0
Fixed Carbon	41.8	43.7	56.0
Ash	21.8 - 45.4	21.9	
	100	100	100
Sulphur	0.9	0.94	1.2
Higher Heating Value (MJ/kg)	23.6	24.7	31.6
Free Swelling Index	1 - 3		
Rank	High Volatile B Bituminous		

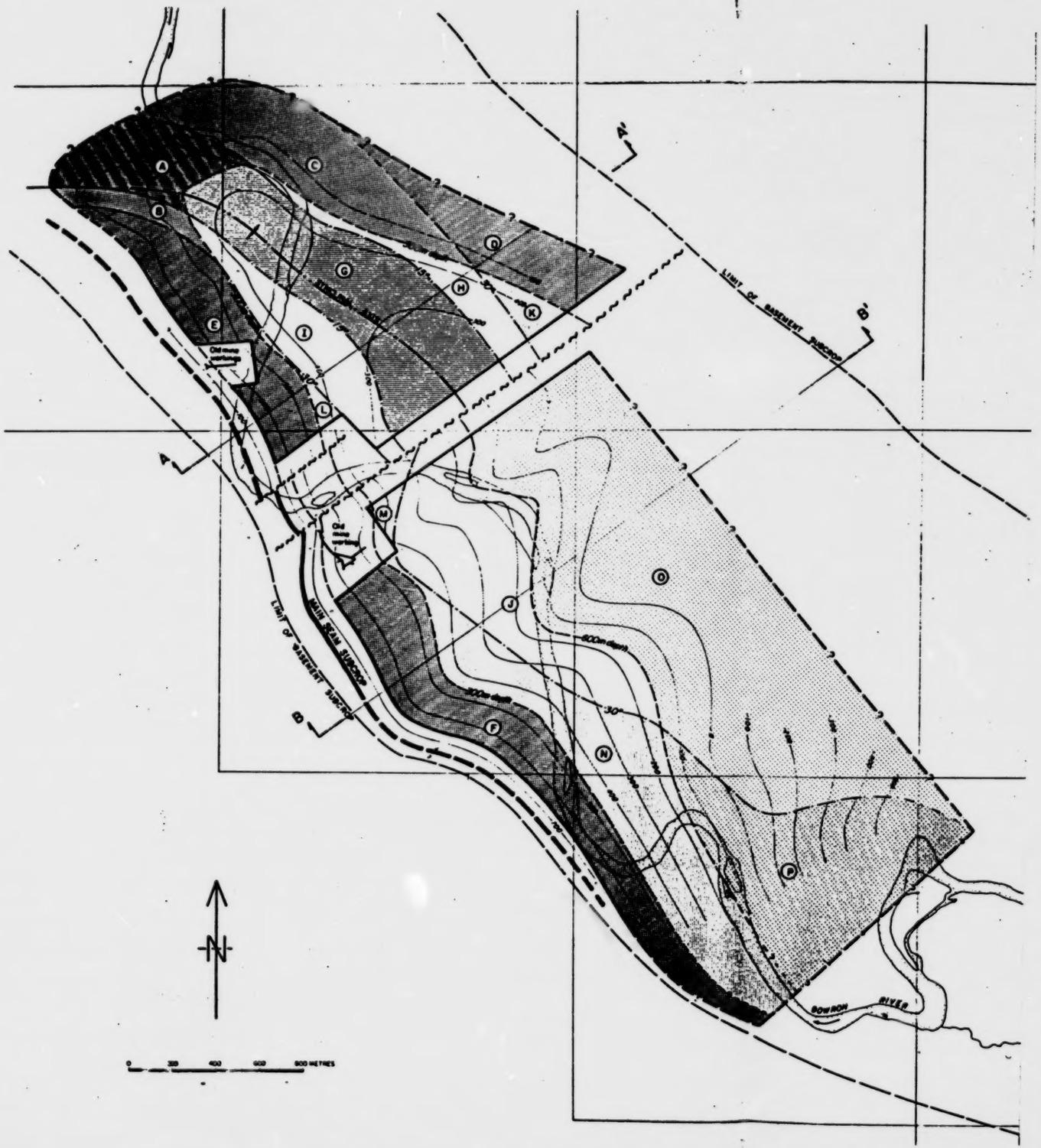


FIGURE 4 BOWRON COALFIELD - STRUCTURAL CONTOURS OF THE MAIN SEAM

Summaries of the reserves contained in the regions marked on Figure 4 and by range of depth and dip are given in Table 3. Reserves for each region of the Bowron coalfield are given in Appendix A.

B. TULAMEEN COALFIELD

1. Location and Physiography

The Tulameen basin is located 4 kilometres south of the small community of Tulameen, 3 kilometres west of the equally-small community of Coalmont, and 15 kilometres west of the city of Princeton in southern British Columbia (Figure 5). This location is relatively near the Inland Natural Gas pipeline.

The Tulameen basin has moderate relief with elevations ranging from 1,100 to 1,450 m. Overburden is variable in depth, but probably averages less than 10 metres. Surface use is primarily for cattle grazing. No major waterways are present over the basin and creeks are sparse.

2. Property and Ownership

Cyprus Anvil Mining Corporation holds 15 coal licenses covering the coal basin having a total area of some 2,500 hectares. The coal license numbers are:

CL 69 - 71
CL 125 - 126
CL 145 - 147
CL 153 - 154
CL 158 - 159
CL 3663 - 3665

3. Proposed Mining

Cyprus Anvil Mining Corporation proposes to mine the Main coal seam on the west side of the basin by open-pit methods. Feasibility studies that show the locations of the open pit and other surface features have been completed (Figure 6). However, initiation of mining is dependent upon an increase in the price of thermal coal and a sales contract.

4. Geological Setting

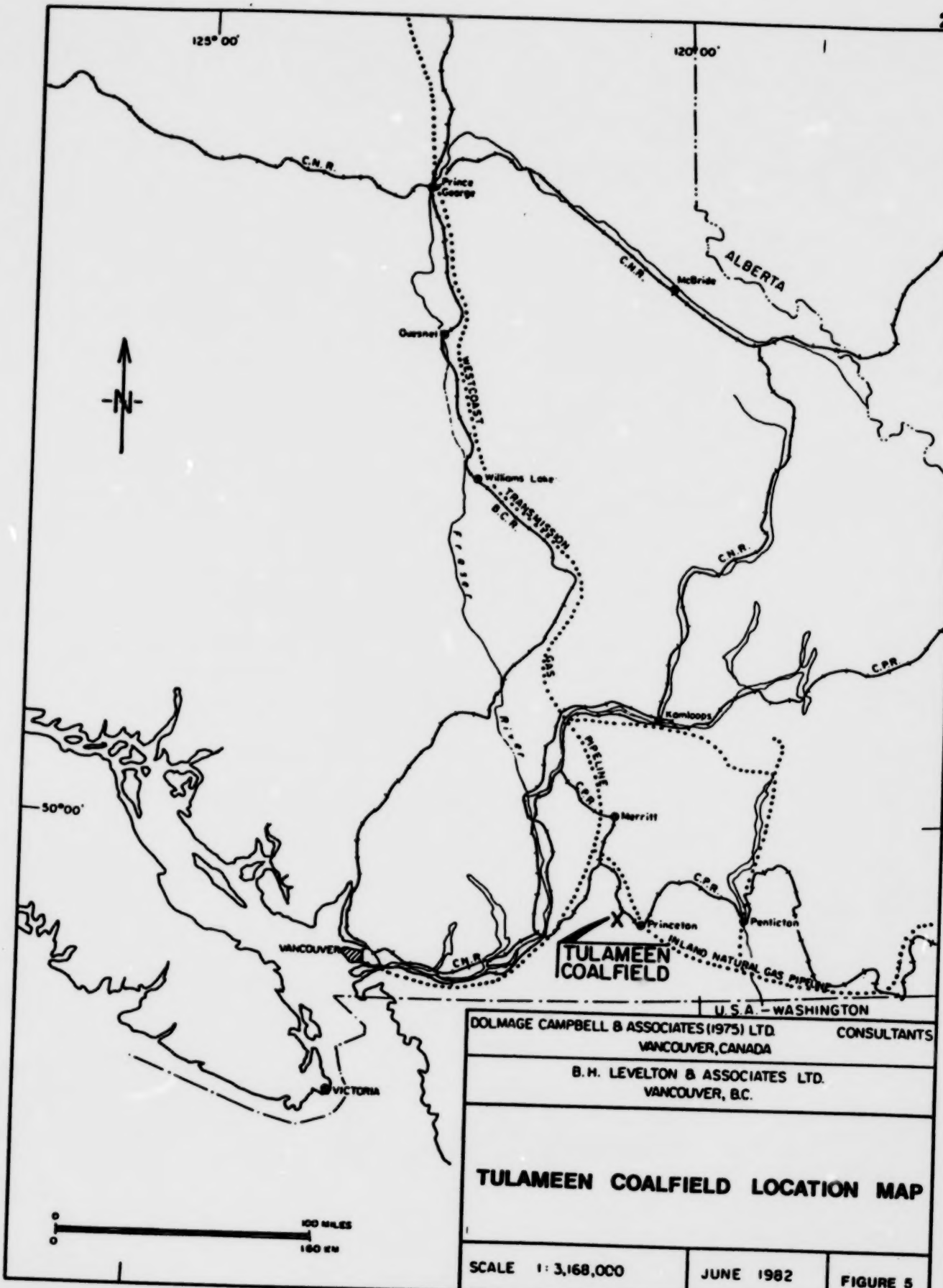
The Tulameen coalfield has been explored by geological mapping, diamond drilling, and underground mining. The geological characteristics of the western and southwestern

Table 3

BOWRON COALFIELD RESERVES

Depth (m)	Seam	Dip < 15°	Dip 15° - 30°	Dip > 30°	Reserve Totals for Depth Ranges (Mt)
100 - 300	Main	*(A) 1.7	(BC) 3.5	(DEF) 8.8	
	Middle	0.4	0.9	1.0	
	Upper	0.3	0.6	0.6	
		2.4	5.0	10.4	17.8
300 - 600	Main	(G) 4.8	(HIJ) 6.8	(KLMN) 6.0	
	Middle	1.5	0.9	0.2	
	Upper	1.1	0.6	0.2	
		7.4	8.3	6.4	22.1
>600	Main	0	(O) 13.8	(P) 5.2	
	Middle	0	0	0	
	Upper	0	0	0	
		0	13.8	5.2	19.9
Reserve Totals For Dip Ranges		9.8	27.1	22.0	58.9

*Regions shown in Figure 4.



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TULAMEEN COALFIELD LOCATION MAP

SCALE 1: 3,168,000	JUNE 1982	FIGURE 5

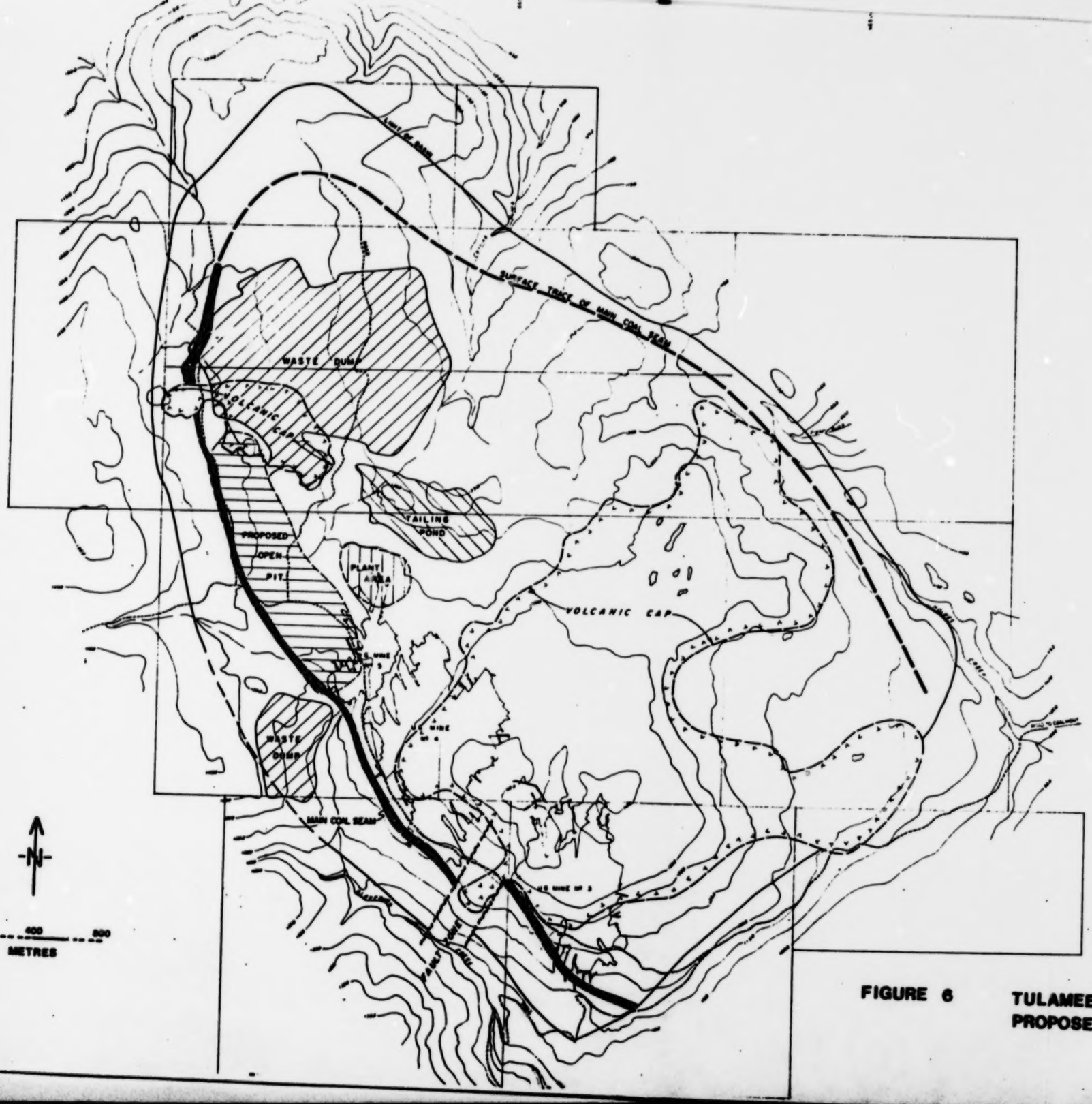


FIGURE 6 TULAMEEN COALFIELD – PAST AND PROPOSED MINING AREAS

sides of the coalfield are particularly well documented, while the central and eastern portions are less well known.

The stratigraphic sequence consists of 580 metres of conglomerate and sandstone overlying 130 metres of coal measure, which, in turn, overlies a 60-metre basal member consisting of sandstone, shale, and siltstone. The coal measure is composed of shale, siltstone, sandy shale, and minor sandstone with interbedded coal and bentonite.

The sedimentary units are folded into a somewhat elongated, dish-shaped basin oriented in a northwest-southeast direction. Depth to the center of the basin is in excess of 600 metres. Faulting has been identified in the southern part of the coalfield.

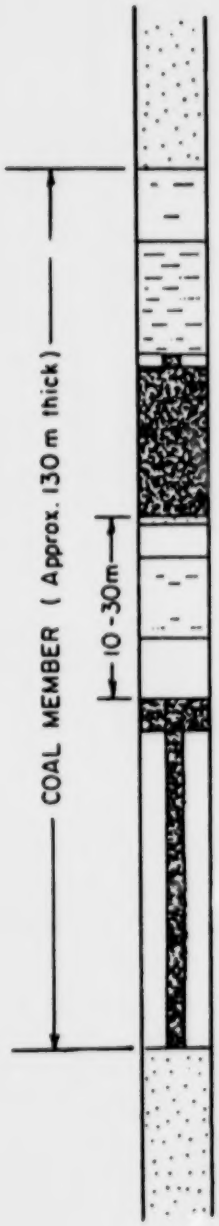
5. Coal Occurrences

The Tulameen coalfield contains two seams of interest, these being the Main and Lower seams (Figure 7). The Main seam has been well explored, tested, and mined; whereas little is known about the characteristics of the Lower seam other than it is "dirty" and averages about 3.5 metres in total thickness. The Main seam appears to be continuous throughout the coalfield, although it has never been tested at depth, and has an average thickness of about 17.5 metres. Some of the coal on the northwest side of the coalfield has been reported from old mining activities to be crushed. This is thought to be a near-surface feature.

The Main seam consists of sections of clean coal, dirty coal, mudstone, and bentonite (Figure 8).

Quality data are available for the Main seam, but not the Lower seam of the coalfield. However, it can be assumed that the quality of the Lower seam is similar to that of the Main seam, except that the ash content is higher. Data relevant to the evaluation of the seams for underground gasification are summarized in Table 4.

The coal in situ has a much higher ash content than the cleaned coal due to shale partings and high-ash coal bands (greater than 50% ash by weight). The ash content of the coal in situ is approximately 37% at 8% moisture content. The volume fraction of the seam occupied by partings and high-ash coal bands is about 12%, resulting in a clean coal thickness of about 15.5 metres.



Upper sandstone (600 metres thick)

Mudstone and shale, blocky breaking

Fissile shale, thinly laminated

Bentonite, thin dirty coal and mudstone

Main coal zone

Sandstone, light grey, medium grained, muddy matrix
Mudstone, dark grey, massive and blocky

Interbedded shale, mudstone, sandy mudstone, distinctive light to dark grey colour banding

Mudstone, massive to medium laminated

Lower coal zone

Interbedded fragmental bentonitic tuff, thin coal seams, and coaly bentonitic mudstone

Lower sandstone (100 - 150 metres thick)

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TULAMEEN COALFIELD

STRATIGRAPHIC SECTION OF THE COAL MEMBER

SCALE : VERT. 1:1000	JUNE 1982	FIGURE 7

Roof	Shale and sandstone (10-20m ?)
1.5 - 2.5	Bentonite; some thin dirty coal and mudstone
2.0-2.2	50-95% clean coal ; dirty coal, minor bentonite
0.3 - 0.6	Bentonite
2.7 - 3.7	Clean coal ; local mudstone partings
0.1 - 1.2	Dirty coal
2.3 - 3.4	Clean coal ; local thin bentonite or dirty coal partings
0.1 - 4.3	Mixed dirty coal , clean coal (0 - 75%), mudstone
0.9 - 3.0	Clean coal
0.3 - 1.0	Dirty coal , mudstone
1.8 - 4.3	Clean coal
Floor	Sandstone

NOTE : Thickness in metres

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TULAMEEN COALFIELD

STRATIGRAPHIC SECTION OF THE MAIN SEAM

SCALE : VERT. 1:100	JUNE 1982	FIGURE 8

Table 4

COAL CHARACTERISTICS FOR THE MAIN SEAM OF THE TULAMEEN COALFIELD

	As-Received Basis (wt%)	Dry Basis (wt%)	Dry, Ash-Free Basis (wt%)
Coal Composition:			
Moisture	13.2		
Volatile Matter	27.0	31.1	38.5
Fixed Carbon	43.2	49.8	61.5
Ash	16.6	19.1	
	100	100	100
Sulphur	0.6	0.69	0.85
Higher Heating Value (MJ/kg)	22.09	25.4	31.5
Free-Swelling Index	1 - 2		
Rank	High Volatile C Bituminous		

6. Coal Reserves

Reserves were calculated only for the Main seam because the continuity of the Lower seam is untested (Table 5). On the basis of average thickness, the Lower seam would contain about 20% of the Main seam reserves.

Reserves were calculated for all areas within the coalfield according to the parameters stated earlier for buffer zones adjacent to old mine workings and crushed, high-permeability coal areas. In the central, deeper part of the coalfield, the configuration and continuity of the seam are somewhat conjectural because of a lack of exploration data. Reserves for each region of the Tulameen coalfield are given in Appendix A.

Parts of the coalfield having depths of overburden of 100 to 300 m, 300 to 600 m, and greater than 600 m and seam dips of 0° to 15°, 15° to 30°, and greater than 30° are estimated in Figure 9. These results were used for the evaluation of the suitability of the Main seam for underground gasification.

Table 5

TULAMEEN COALFIELD RESERVES FOR THE MAIN STREAM

Depth (m)	Dip < 15°	Dip 15° - 30°	Dip > 30°	Reserve Totals for Depth Ranges (Mt)
100 - 300	---	---	*(1,2) 27	27
300 - 600	---	(5,6) 40	(3,4) 51	91
>600	(11,12) 37	(8,9,10) 62	(7) 8	107
Reserve Totals For Dip Ranges	37	102	86	225

*Regions shown in Figure 9.

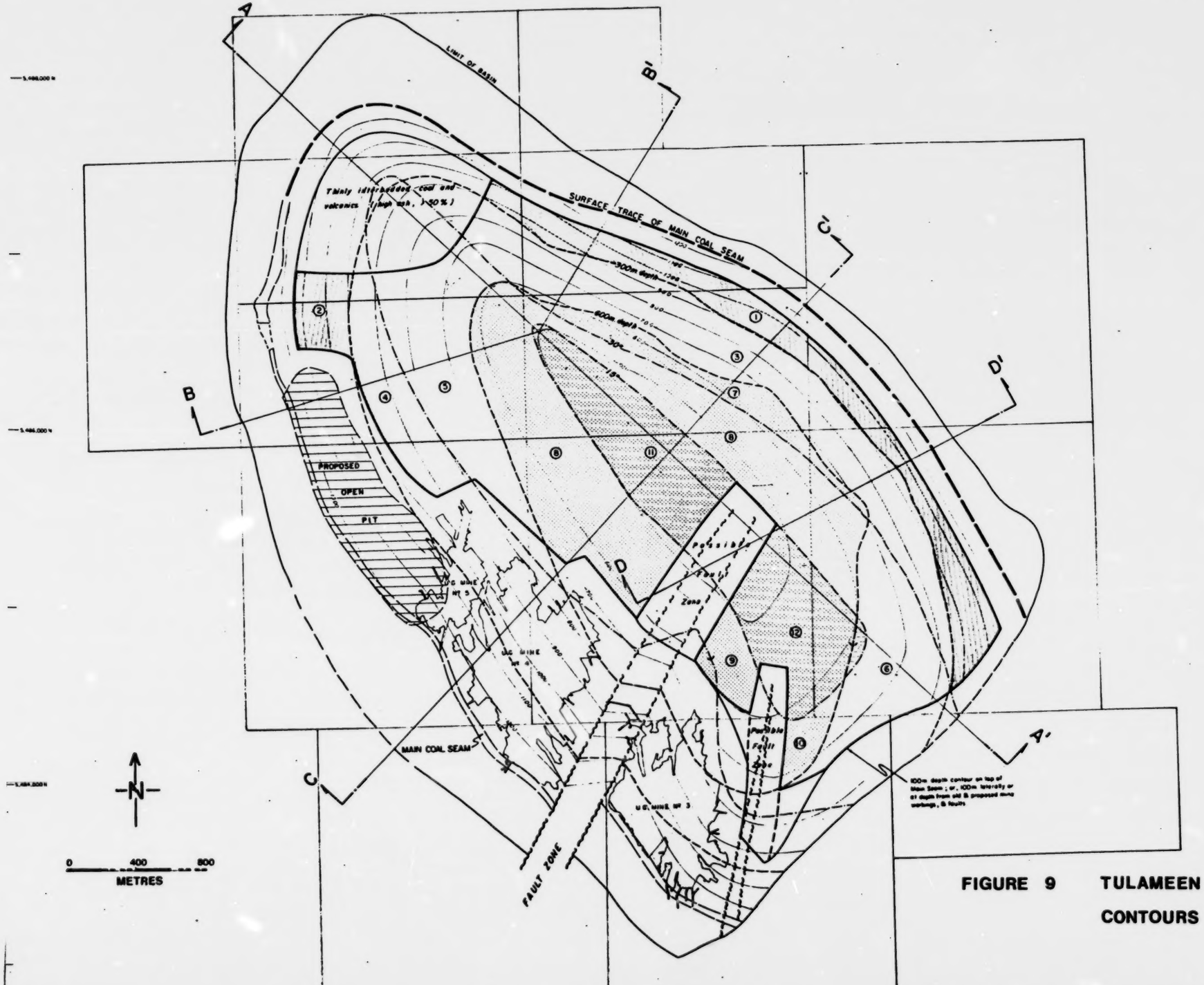


FIGURE 9 TULAMEEN COALFIELD - STRUCTURAL CONTOURS OF THE MAIN SEAM

IV. UNDERGROUND COAL GASIFICATION PROCESSES

A. STATUS OF THE TECHNOLOGY

All commercial-scale experience with underground coal gasification has been limited to the U.S.S.R., and reports on the performance of these plants are incomplete due to their proprietary and political nature. A summary of annual Soviet production for the years from 1950 to 1977 as published in the literature is shown in Figure 10, indicating that only the Angren (lignite) and Yuzhno-Abinsk (bituminous coal) plants have been operating in recent years. Data are not available past 1977. The decline in production of Angren is believed due to low gas heating values, high gas losses, and close well spacing which made the operation economically unfavorable. The Soviets seem to have made little use of process modeling to optimize the process and have not continued to develop new techniques or refine procedures to improve operation (Stephens).

A total of some seventeen field trials of underground coal gasification have been conducted in the United States by the Department of Energy and the private sector. Field tests have also been conducted in Alberta, France, and Belgium. Basic Resources Inc. of Texas licensed the Soviet technology and conducted two tests with air injection to produce low-heating-value gas from lignite. A wide variety of coals and approaches to underground gasification have been used in the field trials, and considerable associated efforts have been made to develop better understanding of the processes involved and, with this, predictive process models.

Since 1981, the United States government has adopted a policy whereby funding of field projects was dramatically reduced, and emphasis was placed on more fundamental, scientific understanding of phenomenon occurring during gasification. The reduction of U.S. funding available for field projects and the general down-turn in the economy have since led to a curtailment or termination of development programs in the private sector. Development programs are still active in Belgium, France, and Germany.

Stephens states that the outstanding problems with underground gasification could be resolved by the 1990s with joint support of government and the private sector. The major technical areas where further understanding is required to achieve a commercial level of operation are:

- effects of subsidence and influx of water from surrounding sediments on gasifier performance;

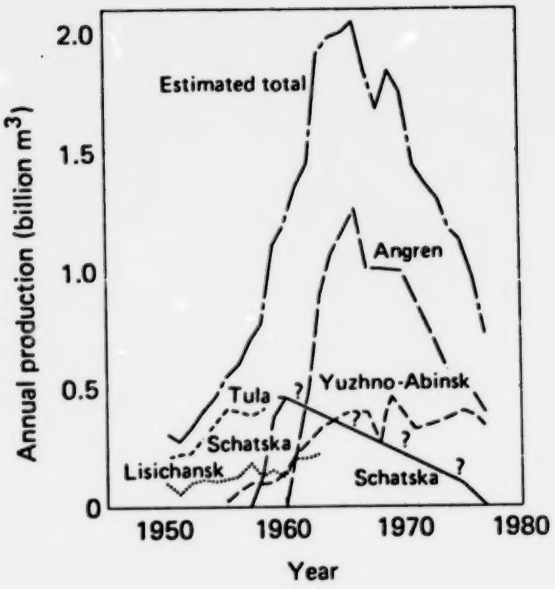


FIGURE 10 ANNUAL SOVIET UCG PRODUCTION 1950 – 1977

- methods of achieving dependable link channels between production and injection wells;

- effects of gasification and subsidence on groundwater flow and quality and surface facilities;

- logistics of operation of multiple-gasifier production systems.

Past experience with field tests of underground gasification shows it to be technically feasible for most coals and site characteristics. There are limits to its applicability, and these limits must form a basis for proper site selection. Underground gasification is not a proven process, and therefore, much field and laboratory experimentation and mathematical process modeling efforts are needed before construction of a prototype commercial plant. With proper selection of a site and adherance to design procedures evolved to date, it is currently possible to construct and operate a field trial involving two to four production wells successfully and with modest control over production gas quality. The next major hurdle in development is the control and operation of several gasifiers concurrently. This configuration is the forerunner of multi-gasifier modules that are necessary for large-scale commercial operation.

B. GASIFIER CONFIGURATIONS

There are many gasifier configurations that have been tried experimentally since development of underground gasification processes was initiated in the early 1930s. Development work undertaken since about 1972 has concentrated on two gasifier configurations, these being called the Linked Vertical Well and Steeply Dipping Bed processes. Some success with a so-called Borehold Producer process, which involves underground mining to gain access to blocks of coal in near-horizontal seams, has been achieved in Great Britain. No further work with this method has been pursued since 1959, primarily because the underground mining that is required for this process is expensive and potentially hazardous for workers due to exposure to toxic gases.

The following discussion gives an overview of the Linked Vertical Well, Steeply Dipping Bed, and Borehole Producer gasifier processes. A thorough discussion of the gasifier configurations and matters relating to the development, operation, and environmental impact of gasification has been given in Phase 1 of an earlier report entitled "A Study of the Suitability of British Columbia and Nova Scotia Coal Resources for Underground Gasification" by B.H. Levelton & Associates Ltd. (Edwards, 1981).

1. Linked Vertical Well Process

A pictorial cross section of a gasifier developed using the Linked Vertical Well process is given in Figure 11. The essence of this method is the use of vertical or nearly-vertical injection and production wells spaced some distance apart. In this case, the shape of the gasified region between the two wells resembles a teardrop where the large portion of the teardrop is located symmetrically about the injection well.

The Linked Vertical Well process has only been applied successfully in near-horizontal seams and, consequently, it is not known whether a limit on the dip of the seam exists. Current understanding of the Linked Vertical Well process suggests that the seam dip should be preferably less than about 15°.

Before gasification can proceed, a link channel of high permeability must be formed between the injection and production wells. This channel may be formed either by a technique called reverse combustion or by directional drilling from surface or a mined gallery. Reverse combustion proceeds by flowing air between the two wells under high pressure and igniting the coal at the receiving well, resulting in counter-current migration of the combustion zone toward the source well. The linking rate with this method has been typically about 1.5 to 1.7 m/day in subbituminous and bituminous coals during field trials. Directional drilling from surface gives better control of the location of the link channel than does reverse combustion linking, but requires sophisticated, state-of-the-art drilling and monitoring equipment to deviate the drill hole to run parallel to and in the bottom one-third of the target seam. Directional drilling becomes increasingly more economical as the length of the useable portion of the link channel increases.

Upon completion of the link channel, the gasifier is ready for gas production. To begin production, coal is ignited in the vicinity of the injection well, and the rate of injection of air or oxygen is increased to the desired level. Coal is consumed progressively as the gasification zone migrates toward the production well. Recovery of the full, vertical cross section of the seam results as the coal fractures and falls under gravity forces forming permeable rubble on the floor of the seam. More complete gasification of coal occurs as subsidence of overburden collapses any developing open channels, maximizing gas/solid contact.

Toward the end of the lifetime of the gasifier, most of the coal between the injection and production wells has been

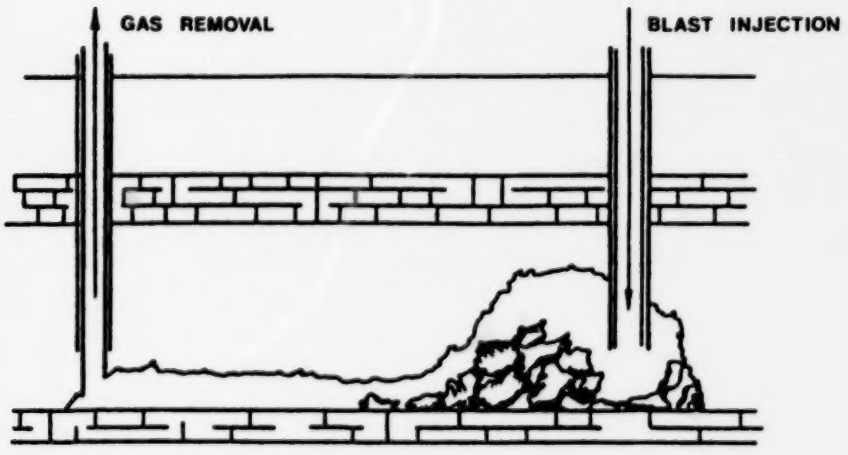


FIGURE 11 LINKED VERTICAL WELL PROCESS

consumed, and increasing amounts of injected oxygen passes through the gasifier unreacted and exits in the product gas. This is usually accompanied by a progressive decrease in the heating value of the product gas. To continue production, another interconnected gasifier with an attendant link channel must be brought online. The procedure for operation of an array of parallel gasifiers in a horizontal seam is illustrated in Figure 12. In this example, it is assumed that parallel link channels have been directionally drilled from surface. Vertical injection and production wells are drilled to intersect the drilled link channel at prescribed intervals. Short link channels between non-intersecting drill holes may be formed by reverse combustion.

The Linked Vertical Well process has been used only in lignites and subbituminous coals which shrink and fracture on heating during gasification. Establishing links in bituminous coals is made more difficult by its swelling behaviour on heating. Swelling, in this instance, tends to reduce permeability and inhibit gasifier operation, as was observed during a field trial in a 2.3-metre thick, 274-metre deep, bituminous coal seam near Pricetown, Virginia, by the Morgantown Energy Technology Center. Consequently, drilling is perceived to be the best method for the formation of link channels in swelling coals.

Drilled link channels have been used successfully in the U.S.S.R. in steeply-dipping, bituminous coal seams; the use of drilled links in this case is simplified by easy access to the seam outcrop for drilling from the surface.

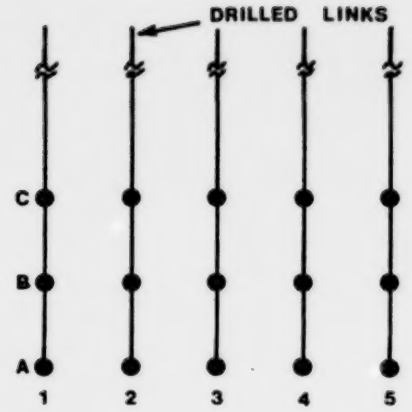
Recognized problems with the Linked Vertical Well process are subsidence, by-passing of injected gases, water influx, and plugging of the gasifier when using swelling coals.

Subsidence has significant environmental impacts on ground use and overlying aquifers. Disruption of the surface topography may affect any existing water courses such as creeks, rivers, and lakes and alter the use that may be made of the land. The selection criteria used in this study were chosen to minimize the effects of subsidence on both the ground surface (i.e. by using coals at depths of greater than 100 m) and nearby aquifers (i.e. by avoiding seams with major overlying aquifers).

Bypassing of injected gas is not an easy problem to correct since it is not due to any one operating parameter. This problem is reduced by sagging of the overburden into the gasifier cavity, a behaviour associated with shales and siltstone. The beneficial nature of these rock types has been incorporated into the selection criteria.

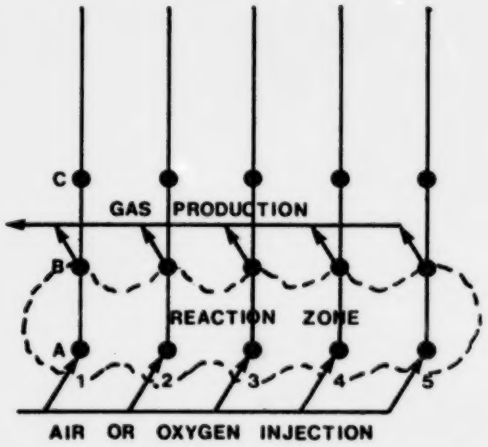
Stage 1

Drill link channels from surface to pass near bottom of seam. Intersect links with vertical wells A1, A2, etc.



Stage 2

Ignite coal at Row A. Gasify with injection at Row A and production at Row B. Continue until coal is exhausted.



Stage 3

Advance injection to Row B and production to Row C. Drill new production Row D for next advancement.

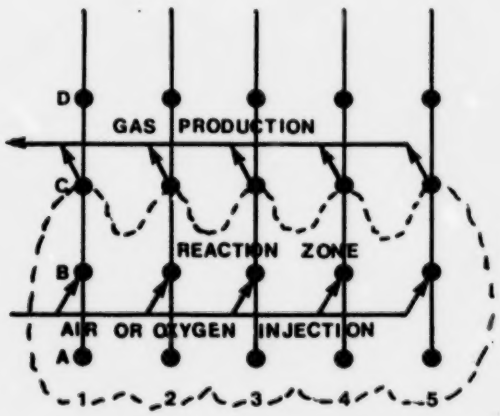


FIGURE 12 ILLUSTRATION OF A PROCEDURE FOR CONTINUOUS MIGRATION OF UNDERGROUND GASIFICATION

Water influx from nearby aquifiers, including the coal seam, affects the performance of the gasifier by altering temperatures in the reaction zones, and by making steam available for chemical reactions. The selection criteria were based on results of field tests that indicate the preferred range for water influx. Unfortunately, insufficient data and theory are available to predict the water influx rate to expect for a given coal seam and surrounding sediments, and it is only possible to speculate on the influx rate that may be encountered.

The swelling behaviour of bituminous coals makes it necessary to use drilled holes for link channels. Free-swelling indices greater than 5 have been classed as poor in the site-selection criteria to recognize the problems associated with high-swelling coals.

2. Steeply Dipping Bed Process

A pictorial view of the basic layout of process wells relative to the gasified region in the coal seam is given in Figure 13 for the Steeply Dipping Bed process. The vertical injection well shown in the end view of Figure 13 may be used when subsidence of the overburden is not so severe as to destroy the well casing. For thick seams where subsidence is severe, the slant injection well running beneath the seam is used. In both cases, the injection well is cased over its entire length.

The production well enters the coal seam at some depth below surface that sets the upper extent of the gasified region. For the remainder of the length of the production well, it passes along through the bottom third of the seam to the maximum depth of the gasifier. This well is cased to where it enters the coal seam.

Injection and production wells may be offset by half the well spacing as shown in Figure 13, although the advantage of this arrangement has not been proven. This well pattern has reportedly been used in the U.S.S.R.

The first stage of development of the gasifier is the formation of a link channel between the injection and production wells. If the injection and production wells are aligned in plain view at surface, then it is likely that a short link channel, in addition to the production borehole, will be needed to connect the ends of the wells which may have strayed from their intended targets during drilling. This short connecting link may be formed readily using the reverse combustion linking techniques. For offset injection and production wells, formation of link channels between a parallel array of

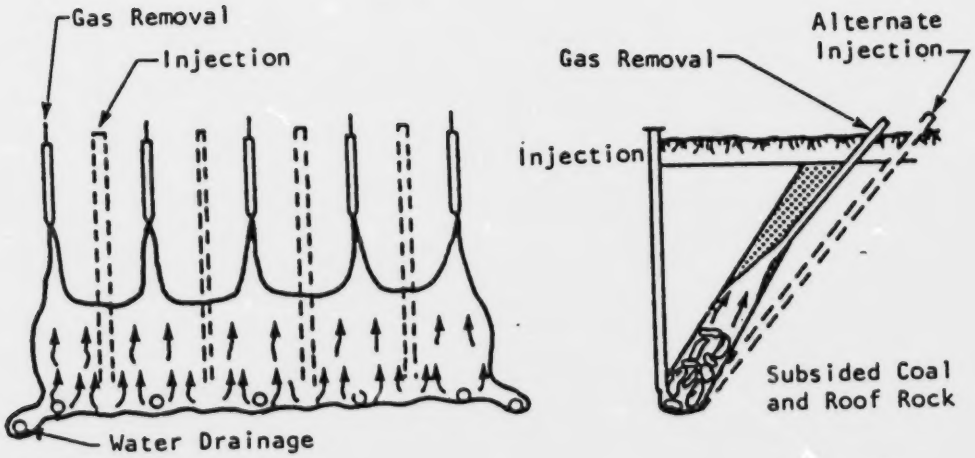
wells is more involved. Link channels may be formed using either directional drilling or reverse combustion. Both of these techniques were used in the plants in the U.S.S.R. In experiments by Gulf Research and Development Co. in a steeply-dipping, subbituminous coal seam, short reverse combustion links were formed between the injection and production wells before gasification proceeded.

The Steeply Dipping Bed process is generally believed to be limited to seams having dips greater than about 40° to 45°. The limit on seam dip is imposed more by the high cost of drilling slant holes to a desired depth in seams with a low dip than by the behavior of the coal during gasification. Experience has demonstrated that the Steeply Dipping Bed process may be used in seams having dips of 30° to 75° without serious difficulties. Seams having a higher dip are more difficult to gasify because of the large vertical displacement that may occur upon subsidence of overburden. Cases have been reported in the Soviet literature of formation of vents to the surface during gasifiction of steeply-dipping, thick seams near surface.

Once a link has been established between the injection and production wells near what is to be the bottom of the gasifier, gasification can proceed by injecting air or oxygen through the injection well. Coal is consumed as the reaction zones migrate up-dip, consuming the coal surrounding the production borehole. As coal drys and fractures, it falls to the floor of the gasifier, forming a bed for gasification. Subsidence promotes this activity and reduces the size of open channels formed as coal is consumed.

Coal is gasified from a region in the vicinity of the injection well and up-dip over an area that tapers down to the size of production well. The upper extent of the gasifier is set by the location of the casing of the production well. The lateral extent of gasification depends on many factors, including seam thickness and gas-injection rate.

Several injection wells may be drilled to intersect the production well at intervals set to optimize gasifier performance and coal recovery (Figure 14). In this case, gasification is initiated at the bottom of the region to be gasified. Alternate injection wells are brought onstream once they are reached by the migrating gasification zones. Because the drilled production borehole offers a permeable path for gas flow, the spacing between injection wells can be increased to upwards of 45 m by current estimates, though reports exist of distances of 110 m that were tried in the U.S.S.R. Lateral well spacing used in the U.S.S.R. has ranged from 25 to 35 m at one plant gasifying a fairly thin (0.4 to 1.5 m) seam



Note: The alternate injection well is used to avoid disturbance by subsidence.

PLAN VIEW

END VIEW

FIGURE 13 LAYOUT OF WELLS FOR THE STEEPLY DIPPING BED PROCESS

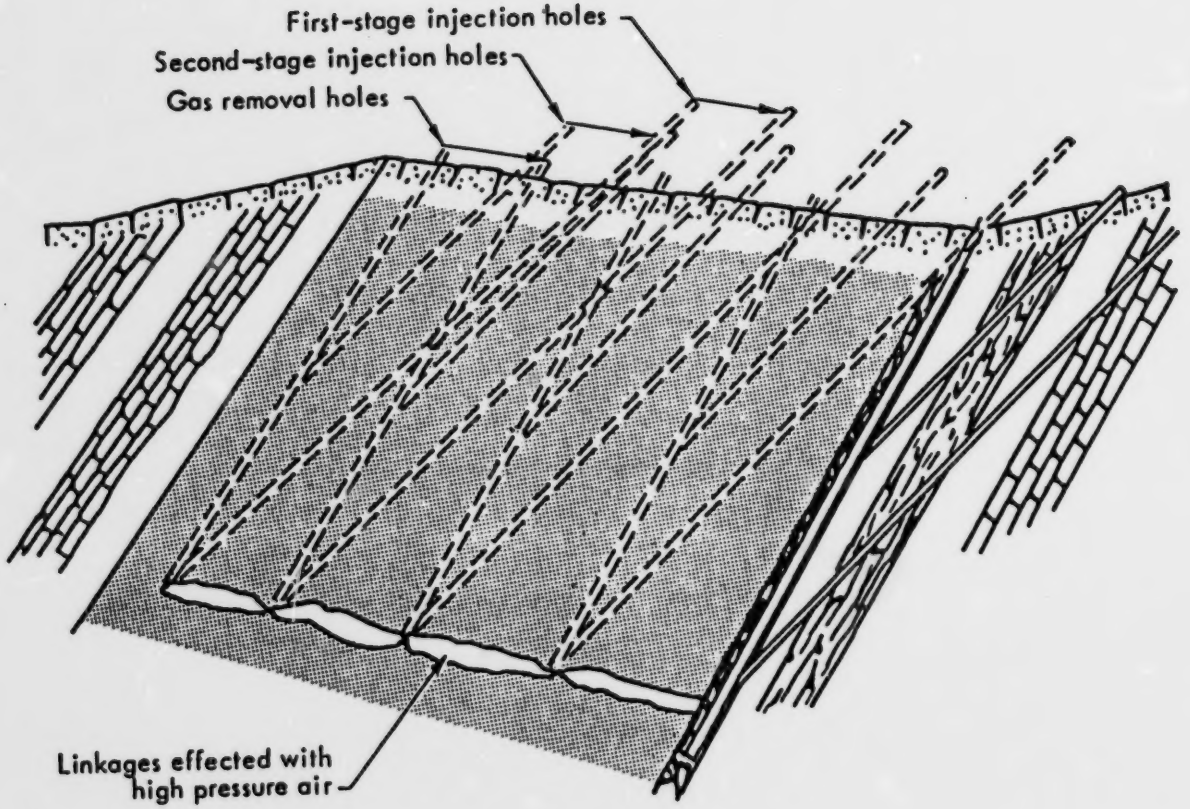


FIGURE 14 PREPARATION OF A STEEPLY DIPPING SEAM USING MULTIPLE INJECTION POINTS

dipping at 20° to 60°. Wider lateral spacing may be used with thicker seams due to comparatively small heat losses.

The Steeply Dipping Bed process has been used most extensively in swelling bituminous coal seams in the U.S.S.R. Gasification has been conducted in these seams using air primarily, though some trials have been conducted with air enriched with oxygen and with steam and oxygen.

Recognized problems with the Steeply Dipping Bed process are essentially identical to those for the Linked Vertical Well process: subsidence, bypassing of injected gases, and water influx.

Subsidence over dipping seams is more severe than for horizontal seams due to a greater vertical height of the gasified region. To minimize the effects of subsidence, injection wells may be placed below the seam or drilled at an incline from above the seam to avoid most of the regions subject to subsidence.

Bypassing of the injected gas is more of a problem with increasing seam thickness and dip. This results because of the greater vertical height of the gasified space. The selection criteria used in this study attempt to reduce the impact of subsidence.

Water influx from nearby aquifers and the coal seam itself is more difficult to estimate for steeply-dipping seams than for the horizontal seams due to the complex hydrogeology of the coal seam and surrounding sediments. One unique problem with inclined seams is that there exists a fairly-direct potential communication link with the surface along fracture and bedding planes. Problems may arise if surface water flows to the gasifier along strata that, after subsidence, become connected. Gas leakage to the surface is a potential hazard.

3. Other Configurations

Several configurations have been proposed by developers for alternate means of underground gasification. Only a few of these have ever been tested in field trials, one being the Borehole Producer process. This process was the result of a series of experimental tests conducted from 1949 to 1959 in Great Britain.

The final test of the program in Great Britain utilized the configuration shown in Figure 15 with air injection. Mining was used to form the gallery from which horizontal holes were drilled. The test was conducted in a high-swelling bituminous coal seam having a thickness of only 0.8 m. Many

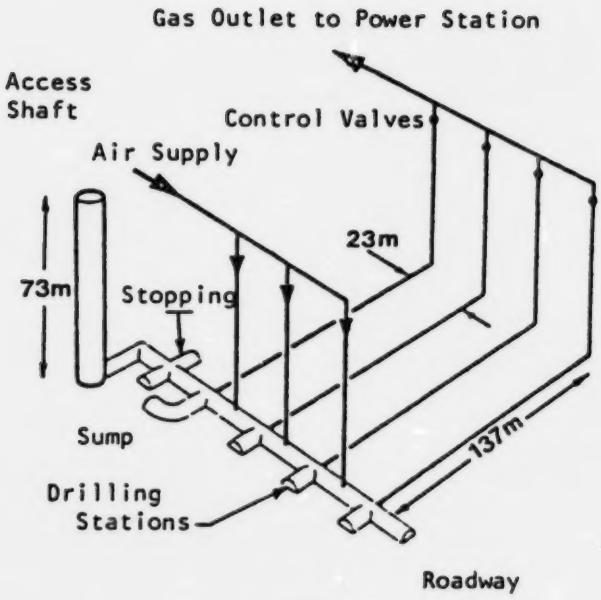


FIGURE 15 BOREHOLE PRODUCER PROCESS FOR THE P5 TEST AT NEWMAN SPINNEY, GREAT BRITAIN

problems with sustaining gas production were encountered due to failures of surface piping and equipment. The heating value of the gas was low (1.8 to 2.2 MJ/m^3) and had to be burned with auxiliary oil burners to maintain combustion in a boiler.

No further development of the Borehole Producer process has been conducted. The process uses the same well layout as the Linked Vertical Well process when directionally-drilled links from surface are used and so is expected to have similar gasifier performance.

C. COMPOSITION OF RAW GAS FROM A GASIFIER

Injection of air into the gasifier results in the production of a gas having a heating value of typically 4.5 to 5.7 MJ/m^3 when clean and dry. The heating value of this gas is low because of the presence of nitrogen at concentrations of 50 to 55 vol %. Example gas compositions from field tests using air injection are summarized in Table 6.

A product gas containing only small amounts of nitrogen, typically about 2 vol %, is produced when oxygen is used as the injected gas, resulting in a heating value of 9 to 11 MJ/m^3. If water influx into the gasifier from the surrounding sediments is low, steam may also be injected with oxygen to promote reaction of steam with carbon to enhance the yield of carbon monoxide and hydrogen. Typical gas compositions for product gas from gasification of subbituminous coal with oxygen are also shown in Table 6.

With oxygen injection, the product gas contains primarily hydrogen, carbon monoxide, and methane. The proportions of these gases varies with the characteristics of the site and operating conditions. The tabulated data show the gas to have a hydrogen content ranging from 31.4% to 37%, while the carbon monoxide ranges from 11.3% to 34.0%. A CO concentration of 34% for Rawlins 1 appears unusually high and is not believed to be a typical value. Excluding Rawlins 1 data, the CO concentration range is 11.3% to 15.7%, resulting in a H_2/CO ratio for the gas of about 2.5%. A value of this magnitude is advantageous for use of the gas for synthesis of synthetic natural gas and methanal.

The quality of the product gas deteriorates over the lifetime of the gasifier, being high at the start due to the contribution of pyrolysis gases, and low toward the end due to bypassing of injected gas along open channels and the increased loss of heat from the gasifier. The effect of this deterioration in gas quality may be mitigated by appropriate phasing of parallel gasifiers, thereby, averaging the gas quality.

Table 6

COMPOSITION OF GAS PRODUCED BY UNDERGROUND GASIFICATION

Operation, Injection Gas	Seam Characteristics	Product Composition (vol %, dry)		
Angren, U.S.S.R.	lignite	H_2	18.7	
1957 - Present	4 - 24 m thick,	CO	6.0	
Air Injection	110 - 250 m deep	CO_2	18.6	
	dip 5° - 15°	CH_4	1.9	
		C_2-C_4	--	
		H_2S	0.45	
		N_2	54.35	
Hanna I, WY	subbituminous coal	H_2	17.3	
180-Day Test	6.8 m thick,	CO	14.7	
1973 - 1974	90 - 120 m deep	CO_2	12.4	
Air Injection	dip 6° - 9°	CH_4	3.3	
		C_2-C_4	0.6	
		H_2S	0.1	
		N_2	51.6	
Hoe Creek 3	subbituminous coal	H_2	37.0	
47-Day Test	7.6 m thick,	CO	11.3	
1979	38 - 50 deep	CO_2	44.0	
Oxygen Injection	dip 0°	CH_4	5.1	
		C_2-C_4	--	
		H_2S	--	
		N_2	1.8	
			Air	Oxygen
Rawlins 1	subbituminous B coal	H_2	12.7	31.4
35 Days	6.9 m thick,	CO	16.2	34.0
1979	depth to 122 m	CO_2	14.0	29.9
30 Days of Air Injection	dip 63°	CH_4	4.7	2.8
		C_2-C_4	0.49	0.17
5 Days of Oxygen Injection		H_2S	--	--
		N_2	51.9	1.6
Rawlins 2	subbituminous B coal	H_2	32.9	
90 Days*	6.9 m thick,	CO	15.7	
1981	depth to 168 m	CO_2	30.3	
Oxygen and Steam Injection	dip 63°	CH_4	19.7	
		C_2-C_4	0.87	
		H_2S	0.18	
		N_2	0.21	

Table 6 (continued)

COMPOSITION OF GAS PRODUCED BY UNDERGROUND GASIFICATION

Operation, Injection Gas	Seam Characteristics	Product Composition (vol %, dry)	
Yushno-Abinsk U.S.S.R. 1955 - Present Air Injection	bituminous coal 23 seams 2 - 9 m thick, depth to 500 m dip 55° - 70° swelling coal	H_2 CO CO_2 CH_4 C_2-C_4 H_2S N_2	13.5 12.7 11.5 3.8 0.1 0.01 58.1

* Planned duration; data for gas composition are experimental values.

The produced gas contains a variety of particulate matter and condensible hydrocarbons along with typically 25 to 35 vol % water vapour. In all tests of the process, erosion of product gas piping by entrained particulate matter has been a problem. Current practise is to remove the coarse particulate matter (>10 um) from the gas as near as possible to the production well. Similarly, heavy hydrocarbons are removed before transport to processing facilities to avoid condensation in transport piping.

Field data for the production rate and composition of tars from underground gasification have not received much attention to date and, for this reason, have not yet been published in a correlated form. Simbeck et al have concluded that the quantities of byproducts, such as tars and oils from an underground coal gasifier, can be expected to be similar to that for surface, fixed-bed gasifiers. Data for tar loadings measured during field trials in subbituminous coals at the Rawlins and Hoe Creek sites are summarized in Table 7. These data make it evident that gasification with oxygen yields a raw product gas with a lower tar loading than does gasification with air. These tars typically have a higher heating value of about 37,220 kJ/kg (Lindeman et al) and, for the quantities produced from the gasifier, contain about 5% and 10% of the higher heating value of the original coal.

The water condensed with these tars contains numerous contaminants common to coal tars, such as phenols and sulphur. Select results of tests measuring the contaminants present in water condensate samples from the Rawlins 1 field test by Gulf Research and Development Co. are given in Table 8. Other contaminants may also be present. Phenols constitute a serious potential skin-contact hazard, and care would have to be exercised in any plant to minimize exposure. Careful handling practises for contaminated liquids are common to existing coal-tar processing facilities.

D. POTENTIAL COMMERCIAL END PRODUCTS

Underground coal gasification, like surface gasification, yields a gas of low heating value when using air injection, or a gas of medium heating value when using oxygen injection. The applications and commercial products that may be produced from these raw gas streams is subject to few limits. Commercial end products that are of current interest are listed in Table 9. Use of low or medium-heating-value gas for resident fuel is not listed in this table because such a use is effectively prohibited by the toxicity of carbon monoxide present in the gas. There may also be problems in delivery of medium-heating-value gas to industrial users, except in cases where a dedicated pipeline exists for this purpose, since the gas grid serves both residential and industrial users.

Table 7

TAR LOADINGS MEASURED DURING THE HOE CREEK AND RAWLINS FIELD TESTS

Field Test	Injected		
	Coal Rank Gas	Total Tars and Oils vol %, dry	g/m^3
Hoe Creek 1[b]	air	0.2	21.1[a]
2	air	0.2	21.1[a]
3	oxygen	0.1	10.5[a]
Rawlins 1[c]	air	0.2[a]	21.2
	oxygen	0.02[a]	1.8
2[d]	oxygen	0.13[a]	13.7

[a] Assumes a molecular weight for tar of .250 g/mol.

[b] Thorseness and Cena.

[c] Montagna.

[d] Bruggink and Davis.

Table 8

CONTAMINANTS PRESENT IN CONDENSATE SAMPLES TAKEN FROM THE PRODUCT GAS AT RAWLINS 1 DURING AIR AND OXYGEN INJECTION

	Air Injection	Oxygen Injection
Total Sulphur (mg/l)	369	192
Dissolved Solids (mg/l)	4,070	854
Phenols (mg/l)	6,760	2,210
Cyanide (mg/l)	55.8	0.534
Ammonia (mg/l)	40	25
Sulfide (mg/l)	96	22
Organic Nitrogen (mg/l)	5,670	1,680
Arsenic (mg/l)	<0.1	0.21
Total Organic Carbon (mg/l)	8,350	2,200
Chemical Oxygen Demand (g/l)	31.5	10.4
Collection Temperature (°C)	46	43

Source: Montagna

Table 9

COMMERCIAL END PRODUCTS THAT MAY BE PRODUCED VIA UNDERGROUND COAL GASIFICATION

Injected Gas	Raw Product Heating Value	Surface Processing Step	End Product/Use
Air	low	gas cleanup	electricity, industrial fuel
oxygen	medium	gas cleanup	electrictiy, industrial fuel
		gas cleanup and CO-shift	synthesis gas (H2 and CO)
		methanation	synthetic natural gas (SNG)
		methanol synthesis	methanol
		methanol synthesis and M-gasoline synthesis	M-gasoline
		Fisher-Tropsch synthesis	synthetic refinery products

To justify production of synthesis gas, a large, possibly dedicated user must exist and be connected by a dedicated pipeline. This situation does not presently exist in the vicinity of the coalfields considered in this study.

Production of synthetic natural gas is a logical option, since the exisitng distribution network for natural gas may be used and no alteration of existing gas-fired equipment is necessary. Transportation fuels such as methanol, M-gasoline, and synthetic refinery products may also be produced via underground gasification, however, these all utilize more involved processing technology than for SNG or syngas, and for this reason, are higher risk technologies.

V. EVALUATION OF THE SUITABILITY OF THE BOWRON AND TULAMEEN COALFIELDS FOR UNDERGROUND GASIFICATION

A. SUITABILITY CRITERIA AND EVALUATION PROCEDURE

In a previous study (Edwards, 1981), a systematic procedure was formulated to arrive at a numerical rating of the suitability of a coal seam for underground gasification. This rating procedure may be used to screen several candidates and obtain an indication of their relative standings. However, the numerical rating must be augmented by a judgmental assessment of important coalfield characteristics to produce a reliable suitability evaluation.

The criteria used for the suitability evaluation are based on published world-wide experience with underground gasification up to 1980. Developments since that time have not altered the basis for the selection criteria. For this study, a change was made to relax the criteria governing the proximity of abandoned mine workings from 0.5 km to 0.1 km. The criteria was reduced to what is thought to be a more realistic value and one that is also consistent with seam depth criteria. The original value for this criteria was based on inconclusive data and was, therefore, somewhat arbitrary.

The revised evaluation criteria are summarized in Table 10.

B. SUITABILITY RATINGS OF THE BOWRON AND TULAMEEN COALFIELDS

1. Sources of Data

Evaluations of the suitability of the Bowron and Tulameen coalfields for underground gasification were made using geological data assembled specifically for this study (Appendix A), as well as hydrogeological data previously assembled for the earlier study of coalfields in British Columbia (Edwards and Vogwill). The hydrogeological data are the most uncertain, since they are based on general experience in similar geological settings rather than actual site-characterization test data. Estimates of hydrogeological characteristics were made acknowledging their uncertainty to give as realistic an evaluation of the coalfields as currently possible. Modest error in the estimates do not markedly alter the final evaluation of the coalfields.

2. Suitability Ratings

This section presents results of the numerical rating of both the Bowron and Tulameen coalfields. A discussion of the characteristics of the coalfields not amenable to a numerical

Table 10

NUMERICAL PROCEDURE FOR EVALUATING THE SUITABILITY OF A COAL DEPOSIT FOR UNDERGROUND GASIFICATION

Site Characteristic	Weighting Factor	Point System for Suitability				
		Critical	Poor	Uncertain	Fair	Good
		Unsuitable	-2	0	2	4
Coal seam:						
seam depth (m)	1	<100	>600		300-600	100-300
seam thickness (m) (coal only)						
- bituminous	1.5	<2			2-4	>4
- subbituminous	1.5	<2.5	>20		2.5-5	>5
- lignite	1.5	<3			3-6	>6
Coal characteristics:						
coal rank	0.5	all others			bituminous lignite	sub-bituminous
volatile matter (%, daf basis)	1		<25		25-35	>35
moisture content (%, wet basis)	1		>30		0-10 20-30	10-20
ash content (%, dry basis)	1		>35		20-35	0-20
partings (% total zone)	1		>25		5-25	<5
swelling behaviour (FSI)	1.5		>5		1-5	0
Seam permeability						
- horizontal (mD)	1		>1000		all others	10-20
- major/minor horizontal	0.5				all others	2-5
- vertical/horizontal	1		>0.2		<0.2	
Seam dip (deg)	1.5		15-30 >75		<15 or 30-75	
Overburden and underburden geology:						
Overburden geology roof rock, type and thickness	1.5	unconsolidated materials, thickness <10 x seam thickness	all others		Arenaceous shale and siltstone	Argillaceous shale and siltstone

Table 10 (continued)

Site Characteristic	Weighting Factor	Point System for Suitability				
		Critical	Poor	Uncertain	Fair	Good
		Unsuitable	-2	0	2	4
Underburden geology floor rock, type and thickness	1.5	unconsolidated materials, thickness <2 m	all others		Arenaceous shale and siltstone	Argillaceous shale and siltstone
Structure	1		faulted, highly folded		all others	
Hydrogeology:						
- water influx rate (m^3/d)	1.5		>125		35-125	<35
- aquifer in roof rock (?)	1	yes			no	
- aquifer in floor rock (?)	1	yes			no	
Location of site:						
topography	0.5		mountainous		hilly	flat
proximity of inhabited areas (km)	1.5		<30		≥30	
proximity of mine workings (km)						
- abandoned	1		<0.1		≥0.1 or none	
- active	1		<1		≥1	
Size of deposit (Mt)						
- bituminous	1		<58		≥58	
- subbituminous	1		<71		≥71	
- lignite	1		<97		≥97	
COLUMN TOTALS			-43	0	50	60

evaluation procedure are dealt with in subsequent sections on each coalfield.

The geological data assembled for the coalfields are in different levels of detail; for example, coal characteristics are average for the coalfield while seam dip and depth are by region within the coalfield. The rating for the common characteristics of the Main seam in the Bowron coalfield is summarized in Table 11. Total ratings for regions within the coalfield, including the criteria for resource size, are presented in Figure 16. The shallowest areas of the Main seam achieved more superior ratings. The overall rating for the Main seam, based on a sum of ratings for each region in proportion to the resource present, is 52, indicating a fair suitability for gasification. This rating assumes that the total resource present in the coalfield is "fair" for gasification.

A summary of the rating factors for the Tulameen coalfield is given in Table 12 for the site characteristics common to all regions of the coalfield. This partial rating excludes seam depth and seam dip characteristics which vary from region to region. The total ratings for each region of the coalfield, including a fair rating of the resource size, are shown in Figure 17. As for the Bowron coalfield, shallower regions of the coal seam achieve the highest suitability ratings. Weighting the rating for each region in proportion to the resource present yields an overall rating for the Tulameen coalfield of 44, indicating fair suitability for gasification. This rating is below the rating achieved by the Bowron coalfield due to several differences in the site characteristics, including the proximity of inhabited areas (Tulameen and Coalmont), a somewhat more-rugged topography, and a greater proportion of resources at a dip and depth deemed to be somewhat poor for gasification.

As concluded in the previous study, the Bowron coalfield, with a suitability of 52, has a slightly higher suitability for gasification than the Tulameen coalfield (rating of 44). However, the slight advantage of the Bowron coalfield in terms of the rating is eroded by some other more general considerations discussed in the following sections. Consequently, the numerical rating must be considered with discretion and as only a general indicator that serves the important purpose of ensuring the coalseams in both coalfields are not unsuitable for gasification; that is, they pass some minimal standards.

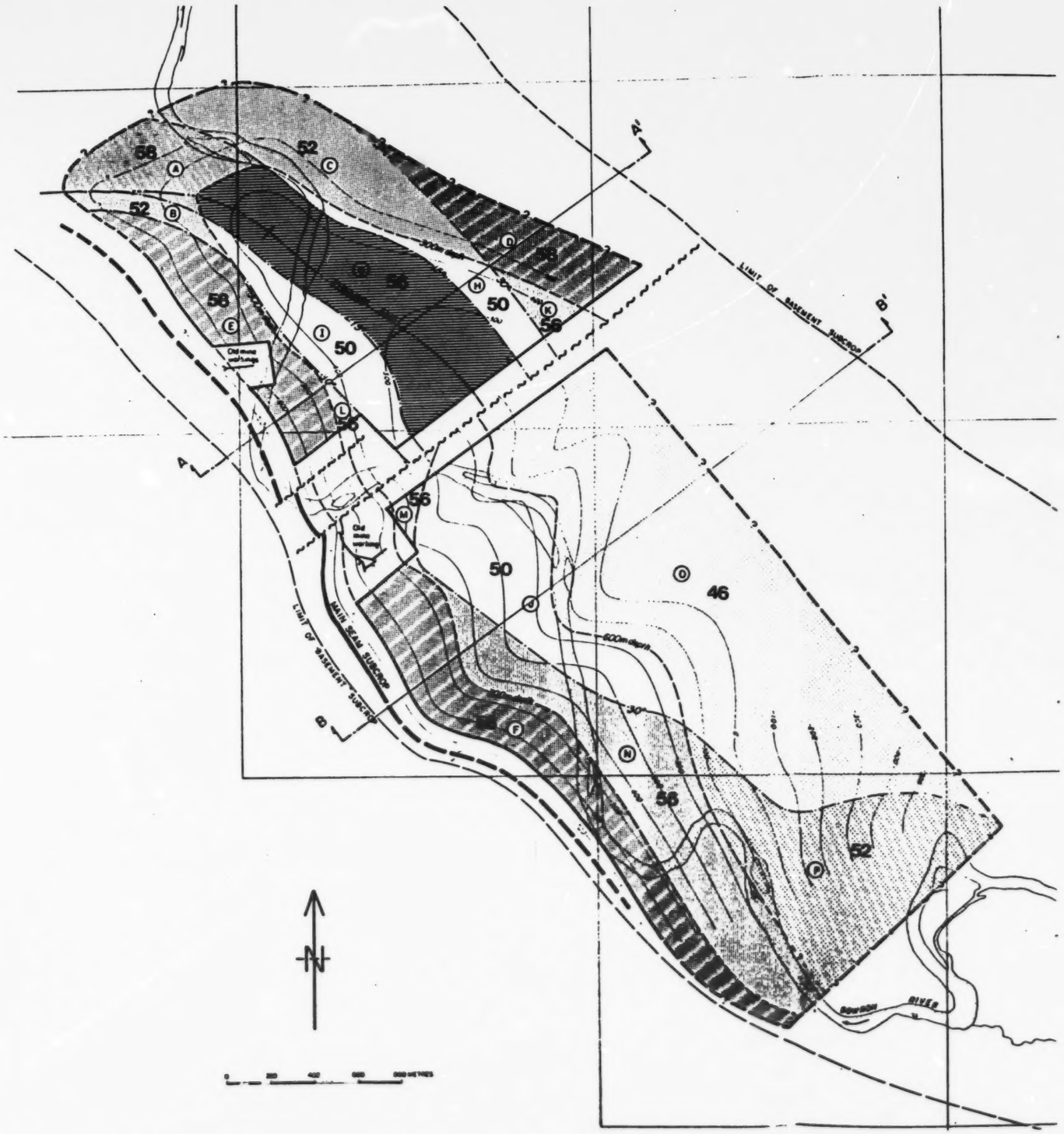
3. Overall Evaluation of the Bowron Coalfield

The overall rating of this coalfield of 52 is a reasonable indication of the fair suitability of the coalfield

Table 11

SUITABILITY RATING TABULATION FOR THE MAIN SEAM OF THE BOWRON COALFIELD

Site Characteristic	Weighting	Poor	?	Fair	Good
		-2	0	2	4
seam depth (m)	1		rated separately		
coal thickness (m)	1.5				4.45
rank	0.5			hvol B bit	
volatile matter (%, daf)	1				44
moisture (%, wet)	1			4.4	
ash content (%, dry)	1			21.9	
partings (%, zone)	1			15.0	
swelling behaviour (FSI)	1.5			1-3	
seam permeability					
- horizontal (mD)	1			20-200	
- major/minor horizontal	0.5		?		
- vertical/horizontal	1			partings	
seam dip (deg)	1.5		rated separately		
roof rock type and thickness	1.5			shale	
floor rock type and thickness	1.5			shale	
structure	1			syncline	
water influx (m^3/d)	1.5				30
aquifer in roof rock?	1			probably not	
aquifer in floor rock?	1			probably not	
topography	0.5				wide valley
proximity of inhabitants (km)	1.5			55	
proximity of abandoned mines (km)	1			none	
size of deposit (Mt)	1			approx 51 (coalfield)	
			0	33	18
PARTIAL RATING:				55	



KEY:

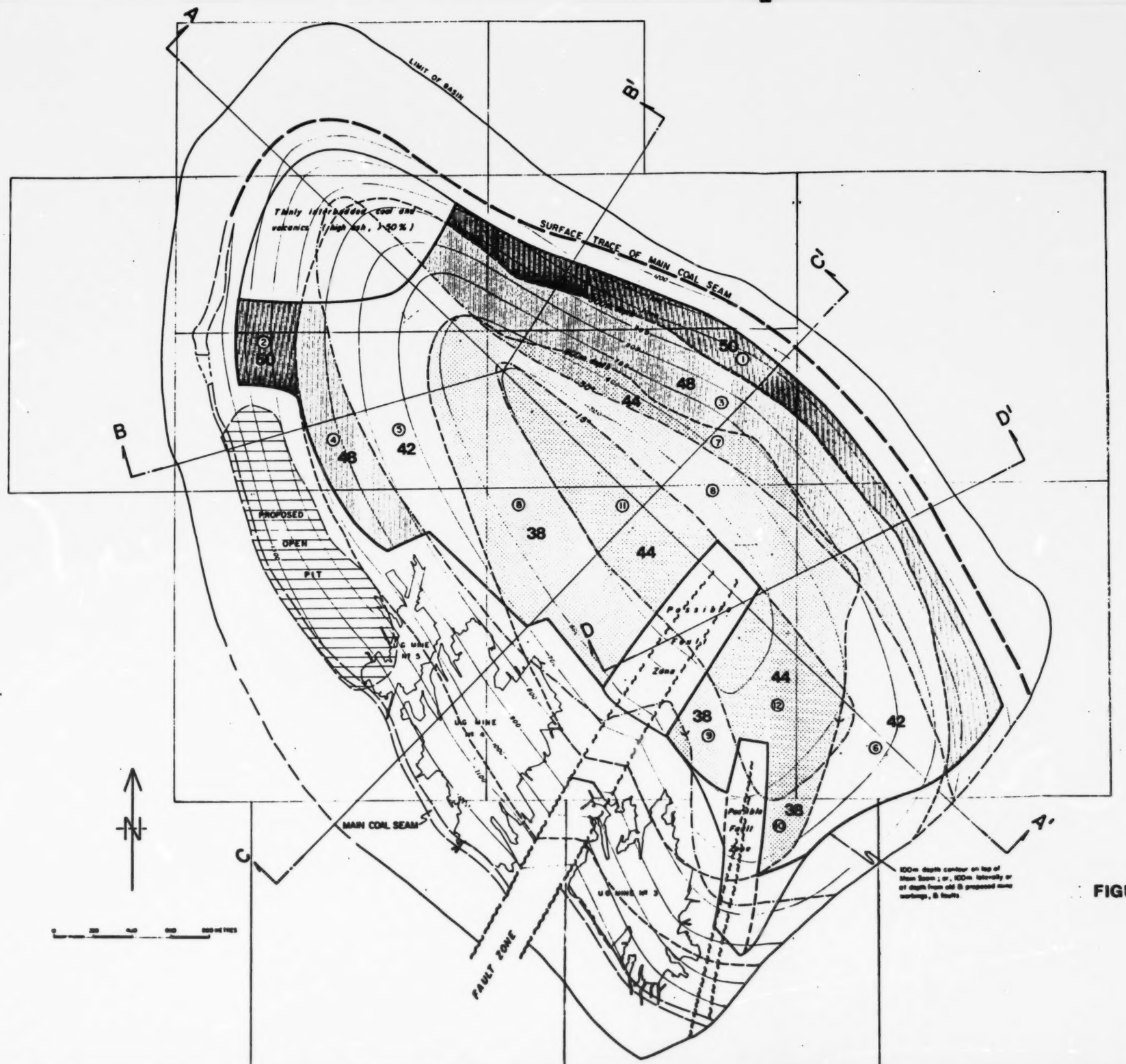
50 RATING INCLUDING COALFIELD RESOURCE

FIGURE 16 SUITABILITY RATINGS BY REGIONS FOR THE BOWRON COALFIELD

Table 12

SUITABILITY RATING TABULATION FOR THE MAIN SEAM OF THE TULAMEEN COALFIELD

Site Characteristic	Weighting	Poor	?	Fair	Good
		-2	0	2	4
seam depth (m)	1		rated separately		
coal thickness (m)	1.5				15.4
rank	0.5			hvol C Bit	
volatile matter (%, daf)	1				38.5
moisture (%, wet)	1				13.2
ash content (%, dry)	1			19-40	
partings (%, zone)	1			12	
swelling behaviour (FSI)	1.5			1-2	
seam permeability					
- horizontal (mD)	1			20-180	
- major/minor horizontal	0.5		?		
- vertical/horizontal	1			partings	
seam dip (deg)	1.5		rated separately		
roof rock type and thickness	1.5			bentonitic shales, sandstone	
floor rock type and thickness	1.5			sandstone, mudstone	
structure	1			basin, some faulting	
water influx (m^3/d)	1.5			61	
aquifer in roof rock?	1			no	
aquifer in floor rock?	1			no	
topography	0.5			hilly	
proximity of inhabitants (km)	1.5	3-4			
proximity of abandoned mines (km)	1			>0.1	
size of deposit (Mt)	1			225	
		-3	0	32	14
PARTIAL RATING:				43	



KEY:

50 RATING INCLUDING COALFIELD RESOURCE

FIGURE 17 SUITABILITY RATINGS BY REGIONS FOR THE TULAMEEN COALFIELD

for gasification from a process standpoint. There is sufficient confidence in the representativeness of the numerical values used in the evaluation procedure to assert that, even upon further field study, the coalfield would likely continue to be generally suitable for gasification.

Some factors are not included in the numerical evaluation procedure but have a bearing on the ultimate viability of the process. In this regard, the main factor for the Bowron coalfield is the presence of the Bowron River over several parts of the coal reserve. This presents the potential for disruption of surface drainage patterns by subsidence, unless gasification of coal beneath the river is avoided, and for trace contamination of surface waters by leakage of gases and condensibles from the gasification area along fractures to surface.

If to avoid subsidence of ground below the Bowron River a buffer area is left ungasified, the remaining coal reserve would be less than the estimated total for the Main seam of 50.6 Mt. This lost reserve is believed to be of minor significance since unexplored areas adjacent to the explored region may contain additional reserves.

The location of the river increases the difficulty of laying gas piping for oxygen feed and for recovery of product gas. No allowance for additional costs incurred because of additional piping requirements was taken into account later in prediction of capital and operating costs for gasification plants.

The Middle and Upper seams of the Bowron coalfield contain an estimated 8.3 Mt and have average thicknesses of about 1.7 m and 1.2 m, respectively. Both seams are less than the preferred thickness of 2 m for bituminous coal; thinner seams have been found to result in excessive heat loss and, consequently, poor gas quality. The spacing between the Main and Middle seams of 15 to 30 m and between the Middle and Upper seam of 15 to 20 m are believed sufficient to avoid interconnection of the seams during gasification, at least sufficient to avoid problems with accidental gasification of overlying seams. In areas where the Upper seam thickness increases to near 2 m, it is conceivable that this seam could be gasified prior to operations in the Main seam either with or without use of common process wells.

In summary, the presence of the Bowron River is a major negative factor and reduces the suitability of the Bowron coalfield, but it still remains a suitable site roughly of equal suitability to the Tulameen coalfield.

4. Overall Evaluation of the Tulameen Coalfield

The weighted average rating for the Tulameen coalfield was 44. This rating incorporates most of the site characteristics having any impact on underground gasification in the Tulameen coalfield. One negative factor is the proximity of inhabitants, specifically inhabitants of the small communities of Coalmont and Tulameen, which are within 3 to 4 km of the coalfield. The proximity of these communities is of concern because of the potential for chemicals evolved by gasification to migrate with groundwater and contaminate potable aquifers. Migration of contaminants from a gasified region has been found not to be significant during or after small-scale field trials. However, reports of noticeable contaminant migration have been made in the Soviet literature. No data were available for this study to ascertain whether potable aquifers are used by local inhabitants.

The proximity of inhabited areas used for the suitability assessment was chosen to be somewhat conservative. It took into account the published Soviet experience and assumed that potable water wells were present. This criteria is uncertain since very little data is available to assess the significance of the problem. Further monitoring of pilot test sites and mathematical modelling of contaminant migration are needed before it will be possible to stipulate the minimum proximity of potable water wells with much confidence.

Only the Main seam of two seams present in the Tulameen coalfield was evaluated. The Lower seam has an average thickness of about 3.5 m, but is dirty and has not been explored in much detail. On the basis of thickness, a reserve of 45 Mt is present in the Lower seam, increasing the total for the coalfield by about 20%. This seam is 10 to 30 m below the Main seam and, therefore, could be gasified; preferably after the recovery of the Main seam. Gasification of the Lower seam before the Main seam could lead to subsidence of the strata below the Main seam and consequent operational control problems when gasification in this seam is undertaken.

The presence of the Lower seam enhances the suitability of the coalfield because of the added resource and the potential to use common process wells for gasification of both seams.

In summary, the Tulameen coalfield has a somewhat higher suitability for gasification than indicated by the numerical rating because of the large resource present in two seams, the small areal extent of the coalfield, and the absence of any surface features that would impede a gasification operation. Additionally, there is no conflict between proposed surface

mining activity and any possible underground gasification operation. Further, the Tulameen coalfield is near the Inland Natural Gas pipeline, a situation that would benefit a plant producing synthetic natural gas.

VI. PROCESS DESCRIPTIONS FOR SYNTHETIC NATURAL GAS AND SYNTHESIS GAS

A. BASIS FOR SELECTION OF END PRODUCTS

Through discussion with Mr. R. Blakely, the end products of principle interest to the B.C. Hydro Gas Group for this study were identified to be synthetic natural gas (SNG) and synthesis gas. SNG is defined for the purposes of this study to consist of nominally 95 vol % methane with the balance made up of nitrogen, hydrogen, carbon dioxide, and water vapour. The higher heating value of the product amounts to 36.3 MJ/m^3. Similarly, synthesis gas is defined to consist of nominally 90% hydrogen and carbon monoxide in the proportion of 2:1, respectively. The balance consists principally of methane with minor amounts of ethane, nitrogen, carbon dioxide, and water vapour. The higher heating value of the syngas is 15.1 MJ/m^3.

An alternate product, and one of lower grade, is low-heating-value gas derived by gasification with air. The major applications for this product are electricity generation by firing in steam boilers and industrial heating. This product was assumed to be of less interest than SNG and syngas, and for this reason, was not analyzed to develop production costs. In the use of low-heating-value gas, costs of transport prohibit medium or long-distance transport. Studies by others conclude that generation of electricity using low-heating-value gas can only be economic when the facility is located within a few miles of the gasification plant.

High-grade liquid products such as methanol and M-gasoline may be produced by further processing of synthesis gas. These products were considered to be outside the terms of reference. However, the syngas considered in this study is suitable for processing to these end products.

B. BASIS FOR PLANT DESIGNS

1. Plant Output Capacity

The output capacity of the SNG and syngas plants were chosen so that all the reserves present in the Main seam of the Bowron coalfield would be exhausted after 20 years of operation at 100% plant factor. The same size of plant was used for both the Bowron and Tulameen coalfields to allow a comparison of product prices on an equal basis. Consequently, only 23% of reserves present in the Main seam of the Tulameen coalfield are ultimately consumed, assuming a 100% plant factor.

Sizing the SNG and syngas plants according to the reserves present in the smaller of the two coalfields results in the following nominal plant-output capacities:

SNG : 1.5×10^6 m^3/d (53×10^6 scf/d)
547.5×10^6 m^3/year;

Syngas: 3.8×10^6 m^3/d (134×10^6 scf/d)
$1{,}390 \times 10^6$ m^3/year.

Approximate coal requirements for other plant sizes are illustrated in Figure 18.

The plant sizes chosen for this study are reasonable for prototype plants, and are similar to plants recently analyzed in two feasibility studies by developers in the United States.

2. Gasification Facilities

For both plant types, gasification proceeds using oxygen, resulting in production of a raw product gas with a heating value of about 12.1 MJ/m^3 at 15°C when dry. Gasification may be conducted using either or both the Linked Vertical Well and Steeply Dipping Bed processes. Figure 19 indicates the resources of the two coalfields present at a dip appropriate for the two processes. In both coalfields, most coal at depths of 100 to 300 m is present at dips of greater than 30° and must be gasified using the Steeply Dipping Bed process. A major portion of the coal in both coalfields has dip less than 30° and a depth greater than 300 m. This coal would be gasified with the Linked Vertical Well process using channels directionally drilled from surface.

It has been assumed that the Steeply Dipping Bed process will be used in both coalfields until coal at suitable dips is exhausted. Subsequently, gasification will proceed using the Linked Vertical Well process. Seam dips in the Bowron coalfield decrease with increasing depth starting at a surface value of near 45° on the west limb. An average seam dip of 38° was assumed for all coal at a depth between 100 and 300 m. For the Tulameen coalfield, an average dip of 50° was assumed to apply over the 100 to 300-metre depth range. The dip of the Bowron Main seam is at the low end of the range specified for the Steeply Dipping Bed process, while the dip of the Main seam in the Tulameen coalfield is similar to that gasified successfully in Soviet plants.

Gasifier design parameters forming the basis for the field operations needed for both the SNG and syngas plants are summarized in Table 13. These values are based on published

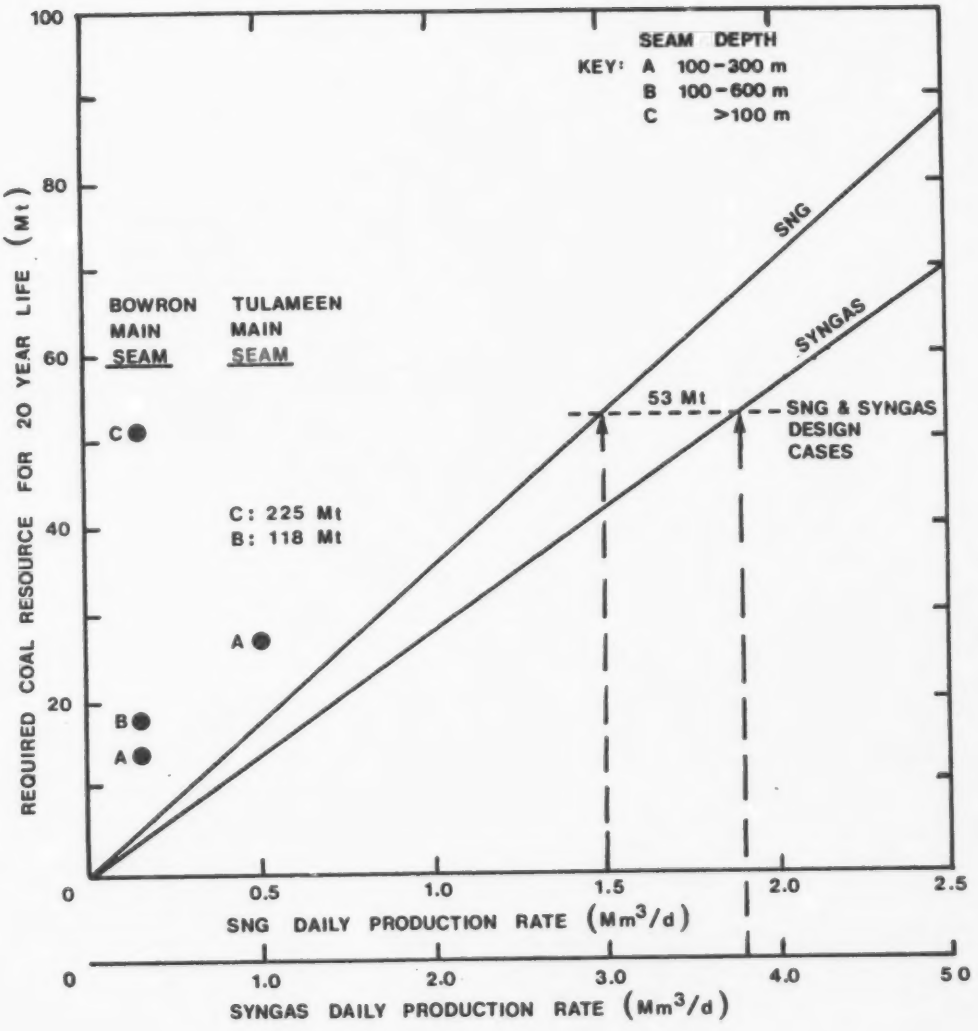


FIGURE 18 APPROXIMATE COAL REQUIREMENTS FOR SNG AND SYNGAS PLANTS

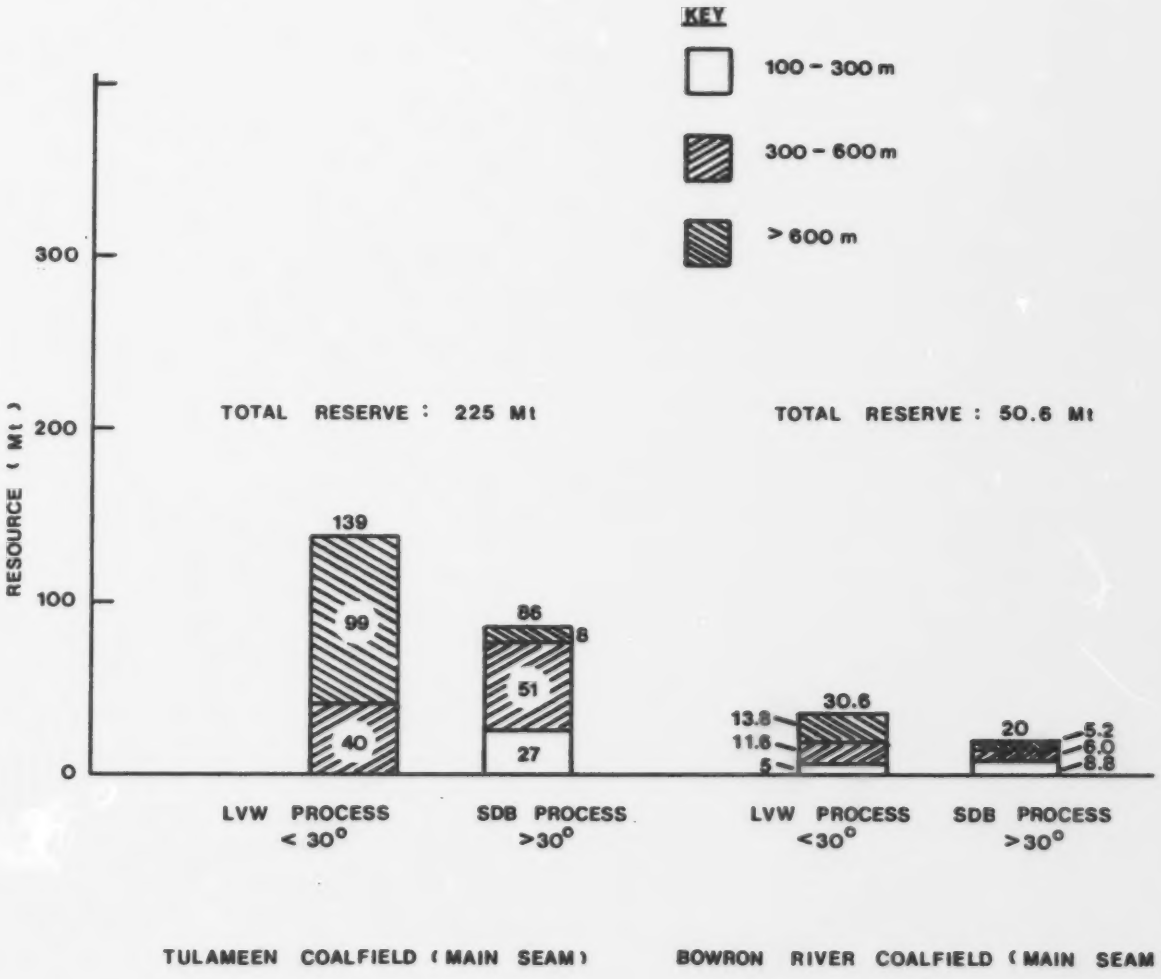


FIGURE 19 COAL RESERVES SUITABLE FOR THE LINKED VERTICAL WELL AND STEEPLY DIPPING BED PROCESSES

Table 13

GASIFIER DESIGN PARAMETERS

Type of Coal	Bituminous
Coal density insitu	1.4 t/m^3
Gasification Process	Steeply Dipping Bed
Well Pattern	Lateral Spacing: 30 m Gasifier Length: 45 m
Process Sweep Efficiency	75%
Cold Gas Conversion Efficiency	75%
Gas Recovery Efficiency	90%
Overall Energy Recovery Efficiency	51%
Linking Method	Directional drilling from surface
Single Well Production Rate	405,000 m^3/d wet gas @ 15°C 300,000 m^3/d dry @ 15°C
Raw Gas Yields	$\frac{1.7\ m^3 \text{ moist gas @ } 15°C}{\text{kg daf coal in gasifier}}$ $\frac{1.26\ m^3 \text{ dry gas @ } 15°C}{\text{kg daf coal in gasifier}}$ $\frac{2\ m^3 \text{ dry gas @ } 15°C}{m^3 \text{ input } O_2 + H_2O \text{ @ } 15°C}$
Injected Gas	Oxygen/Steam 1:1 mol/mol
$O_2 + H_2O$ Injection Requirement	$\frac{0.63\ m^3}{\text{kg daf coal in gasifier}}$ @ 15°C
Injection Gas Conditions	<23 kPa/m depth
Raw Gas Production Conditions	340°C, 500 kPa

reports of Soviet experience and on results of field trials in the United States.

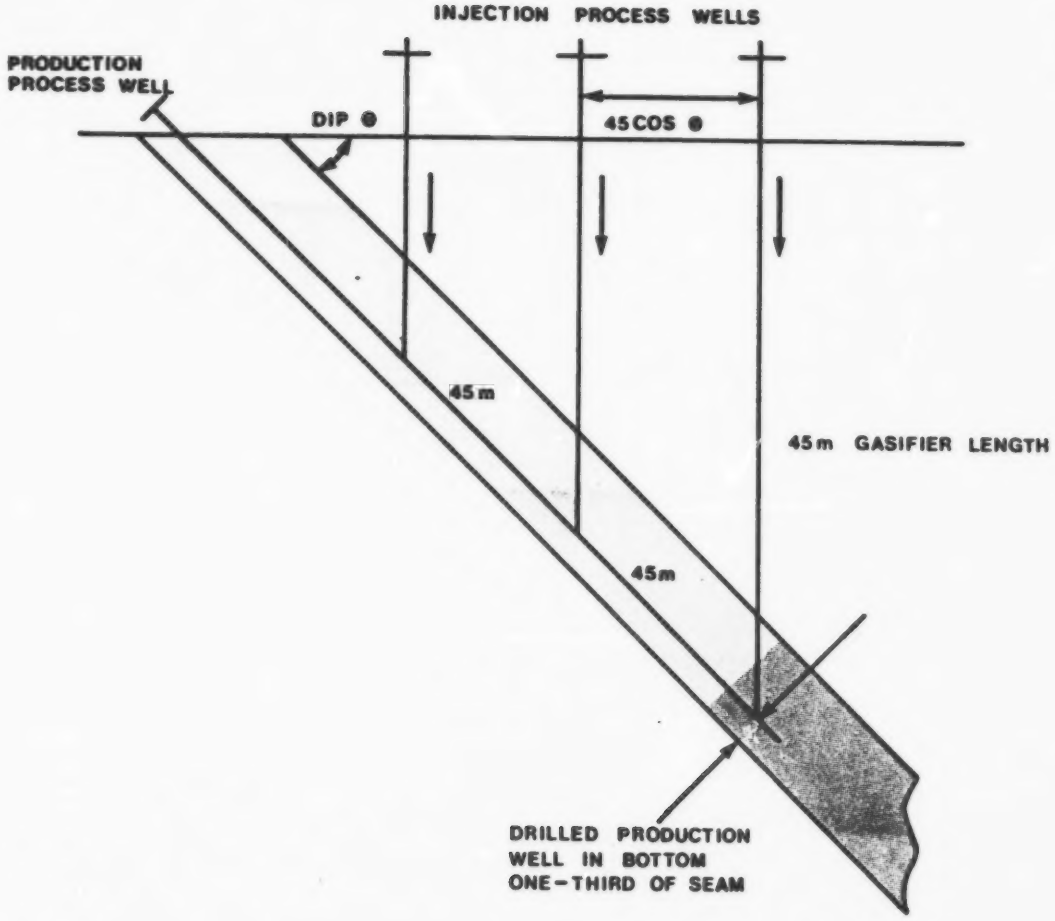
The lateral spacing of gasifiers (along strike) of 30 m was chosen because it is typical of Soviet experience in bituminous coals; it is also less than optimistic values that have been proposed based on field trials in the United States. It is possible that wider spacing of wells could be used, especially in the Tulameen coalfield, since gasifier width has been found to increase as seam thickness increases.

The gasifier length (Figure 20) was set at 45 m, which is a fairly conservative figure compared to the value of 73 m used by Gulf Research and Development Co. at the Rawlins 2 field test in subbituminous coal. This value is similar to the values used in the U.S.S.R. at their operations in bituminous coals and was used for this reason. A 45-metre spacing of process wells along a drilled link in a steeply dipping seam was also suggested in a recent comprehensive study of gasification of bituminous coals in the eastern United States (Williams Bros. Engineering Co.).

The maximum length of an inclined production well drilled from surface to stay in the bottom one-third of the coal seam and reaching to the lowest extent of gasification was set at about 500 m. In both coalfields, the vertical depth at the end of a 500-metre, inclined borehole is near 300 m. The hole length is currently achievable using downhole, mud-driven motors. For example, a set of three horizontal holes were drilled from a kickoff point in a coal seam 300 m deep at Emerald Mine, Waynesburg, PA. A single hole was drilled to the 300-metre depth using a mud motor and diamond bit deviated from vertical 6° every 30 m of drill hole. The three horizontal holes were drilled for distances of 540 m, 900 m, and 966 m.

Developments to improve the control and guidance of directionally-drilled holes are being undertaken by drilling companies for applications in methane drainage, oil recovery, and gas recovery. In the case of underground gasification, future developments will likely enable production of inclined holes having a length greater than the assumed 500 m. It is very likely that the capability of drilling crews would increase dramatically when drilling for underground gasification due to the familiarity of the operators with the geological characteristics of the site. Hence, the 500-metre initial limit of drilling distance is quite a conservative value.

The assumed characteristics of the tar and particulate-matter-free gas produced from the gasifier is presented in Table 14. These data are based on a review of predicted and



NOTE: TO REDUCE WELL FAILURE CAUSED BY SUBSIDENCE, INJECTION WELLS MAY BE DRILLED BELOW THE SEAM OR AT AN INCLINE ABOVE THE SEAM

FIGURE 20 DESIGN SPECIFICATIONS FOR GASIFICATION USING THE STEEPLY DIPPING BED PROCESS

Table 14

RAW GAS CHARACTERISTICS

Composition	Vol %, Moist	Vol %, Dry
H_2	26	35.1
CO	26	35.1
CO_2	15	20.3
CH_4	6	8.1
C_{2+}	0.7	1.0
H_2S	0.3	0.4
H_2O	26	
	100	100

Higher Heating Values: 9.0 MJ/m^3 @ 15°C, moist
12.1 MJ/m^3 @ 15°C, dry

experimental data contained in reports by Hofke et al and Brown for surface gasifiers using bituminous coal and by Martin and Liberatore for underground gasification of bituminous coal. None of the available data applies to the gasification conditions considered in this study; for example, surface gasification uses different coal and process conditions, while the data for the one recent case of underground gasification was done using air injection. The assumed gas composition is believed to be realistic and somewhat conservative in terms of the yield of hydrogen gas (H_2:CO = 1). The hydrogen sulphide content of the gas was based on the assumption that about 50% of the sulphur in the coal is produced as H_2S; field experiments have shown that 25 to 75% of the sulphur in the coal is produced with the raw gas.

3. Coal Characteristics

The coal characteristics detailed in Appendix A and summarized in Chapter III of the main report for each coalfield were used for all calculations. Estimates of coal available for gasification and the productive life of a gasifier were based on the thickness of the seam excluding partings. The gasifier was taken to contain all the coal within 15 m either side of the link channel and between the injection and production wells.

Based on the data for the Main seam of the Bowron coalfield, the lifetime of each gasifier is 29 days when producing steadily at a rate of 300,000 dry m^3/day.

The lifetime of gasifiers in the Main seam of the Tulameen coalfield is about 103 days. This is much larger than for the Bowron coalfield because of the greater thickness of the seam.

4. Surface Processing Facilities

This section discusses some of the general assumptions made to define the SNG and syngas processing facilities. Synthetic natural gas was assumed to be produced at about 7 MPa at the plant gate. Similarly, the synthesis gas was assumed to be available for sale at the plant gate at a pressure of 2.8 MPa.

Byproduct sulphur is available in liquid form for shipment. Some provision is made for storage of sulphur in solid form.

All electric power was assumed to be generated on site using turbogenerators. Some of the generated gas after

cleanup and all of the byproduct oils and tars were used for boiler fuel.

Water required for the plant was assumed to come from recovery of water produced by gasification and from outside sources.

Spare pumps and drivers are provided in the plant at a level of about 50%. Spare units of major process equipment are not included.

C. SYNTHETIC NATURAL GAS (SNG) PLANT

The same design of well layout and surface processing facilities, except for minor features, are used for both coalfields. Therefore, the following discussion of the SNG plant applies to both the Bowron and Tulameen coalfields.

A general schematic of the major process steps is presented in Figure 21. Numbered process streams refer to the table of material flows discussed later under the section on surface facilities.

1. Field Development Facilities

For an output of 1.5 X 10^6 m^3/d of SNG, a raw gas output of 9.8 X 10^6 m^3/d of moist gas is needed from all production wells. This results in a requirement for 25 producing wells under steady operating conditions and a 100% plant factor. For this study, two groups of 13 gasifiers are operating at anytime and discharging into two separate gas-collection pipelines which transport the gas to the surface facility.

The productive life of a gasifier in the Main seam of the Bowron coalfield is about 29 days. Therefore, each gasifier is replaced 12 times per year for a total production requirement of 312 gasifiers per year.

The greater thickness of the Main seam of the Tulameen coalfield increases the productive life of a gasifier to 103 days and lowers the total number of gasifiers brought on-line each year to 91.

Figure 22 presents a schematic layout for two, 13-gasifier trains producing gas for the SNG plant. The production wells are located at the seam outcrop. Vertical injection wells are used for injection of oxygen and steam. There is a potential for damage to vertical injection wells by subsidence of strata immediately above the gasified region. The option of slant-injection wells drilled below the seam to

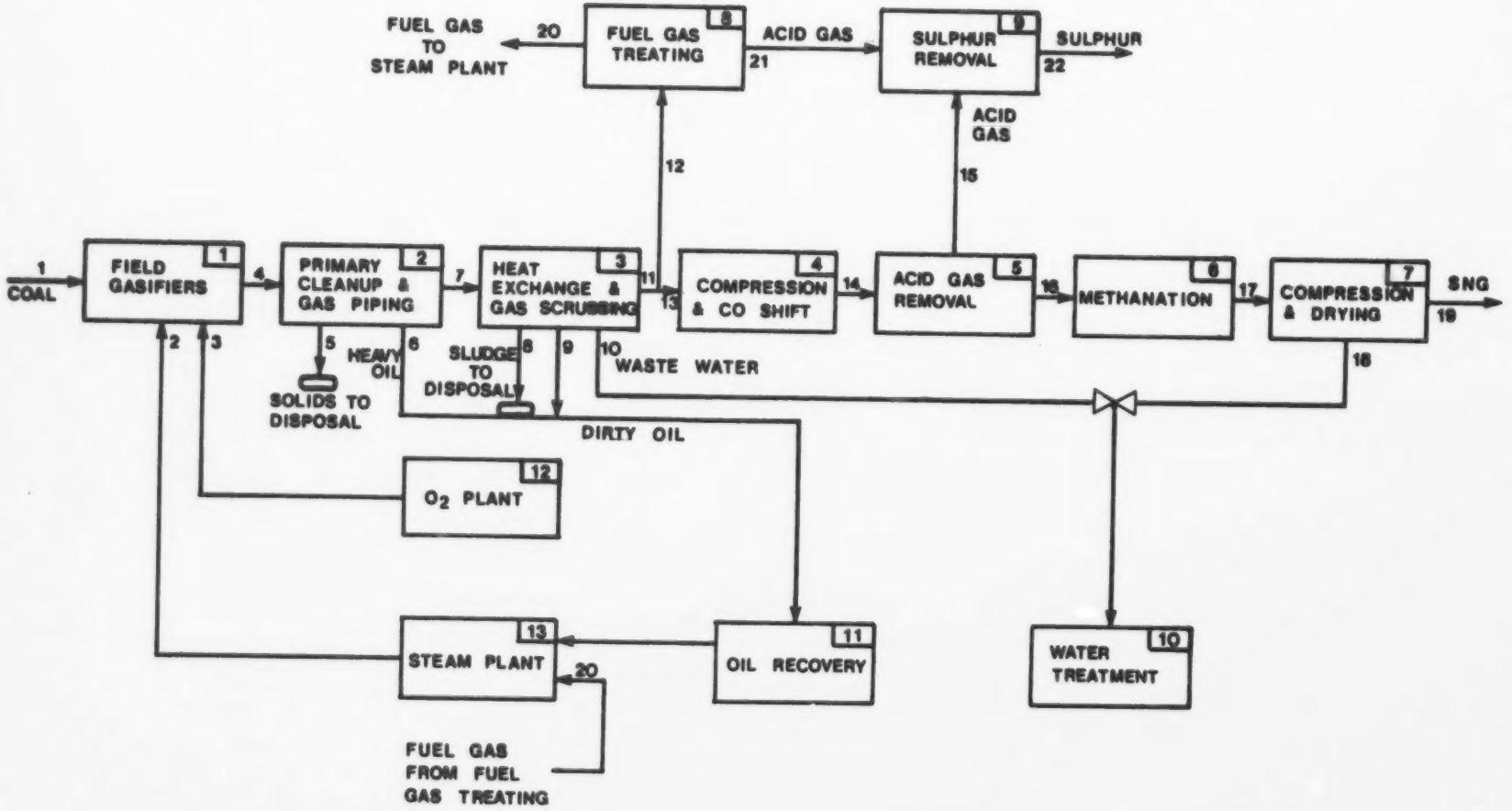


FIGURE 21 SYNTHETIC NATURAL GAS PLANT

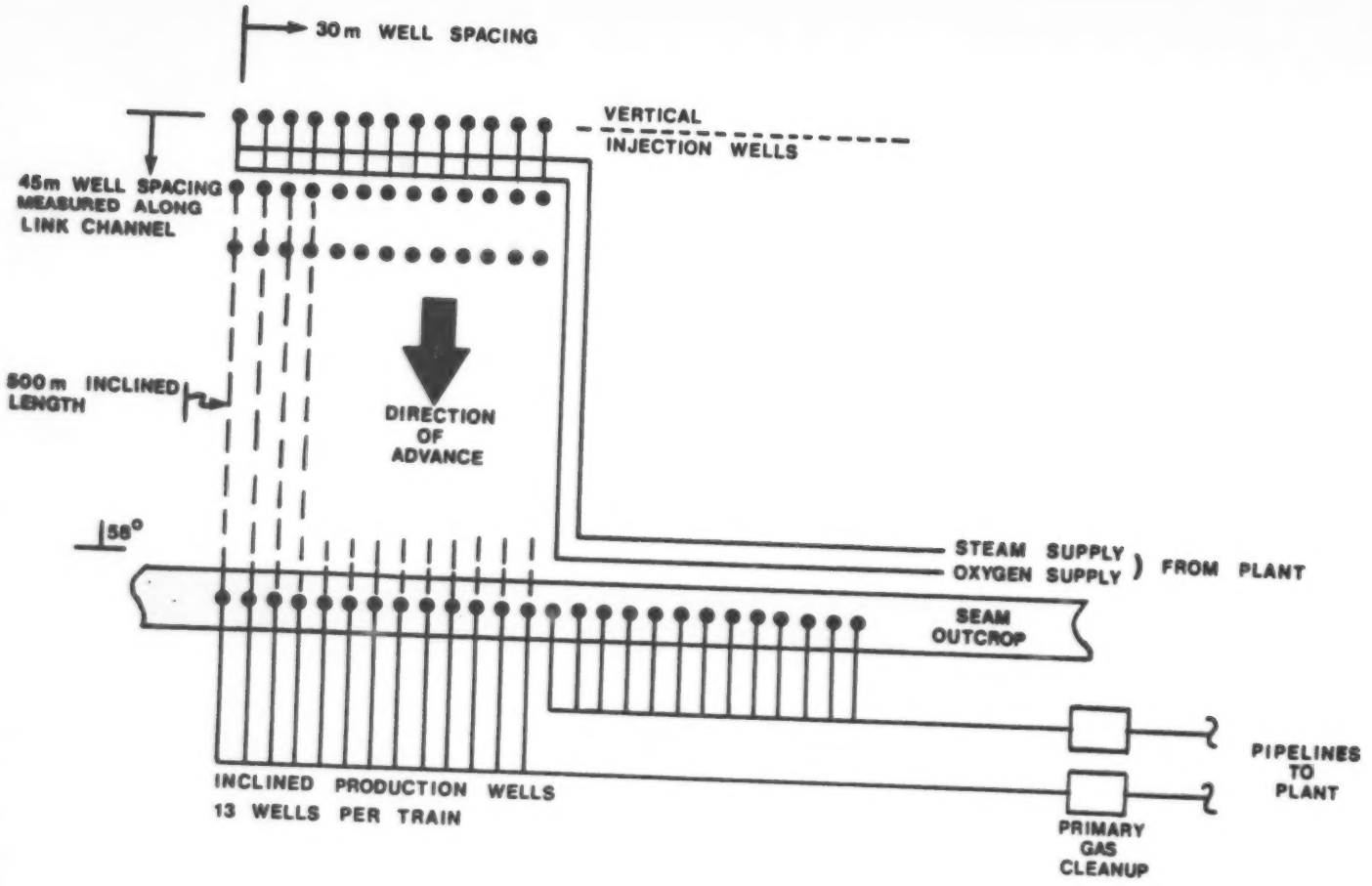


FIGURE 22 SCHEMATIC WELL LAYOUT OF FIELD FACILITIES (PLANT SECTIONS 1 AND 2)

avoid this problem was not chosen because of the shallow dip of the seams in both coalfields, which results in excessively long drill holes. During actual operation, it is likely that experience with subsurface subsidence would enable selection of drilling patterns for deviated wells entering the top of the seam that reduce the effects of subsidence on injection wells.

Production wells are drilled at an incline from the outcrop to run in the bottom one third of the coal seam for a total length of 500 m. The wells are cased (22 cmOD) for 100 m of drilled length from surface, leaving the remaining 400 m as open borehole (11 cm). Heat-resistant grout is used to complete the wells and prevent leakage of produced gas along the borehole to surface. Deeper coal than that accessed by the slant production wells is assumed to be accessed by other wells directionally drilled from surface.

Vertical injection wells are cased (22 cmOD) and grouted to a depth two-thirds through the coal seam. Steam and oxgen are mixed at the well head of the injection well. The injection wells are drilled to intersect the inclined production borehole at the prescribed intervals. Failure to intersect these wells during the drilling process may be corrected by using reverse combustion to form a link channel. The injection wells are complete with isolation valves.

Oxygen and steam are piped separately to the injection wells from the main plant in four lines, a pair of oxygen and steam lines for each 13-well train. The oxygen and steam-distribution manifolds for each set of 13 wells are moved progressively to follow the advance of oxygen and steam injection and the gasification zone up-dip. Oxygen is produced in two separately-packaged air separation plants, one for each 13-well train.

Raw gas from the production wells is directed to two separate trains of primary gas-cleanup cyclones and knock-out drums (plant Section 2) to remove coarse particulate and tar/oil mists. The hot gas is then transported in two parallel 0.9 m O.D. pipelines to the main plant for further cleanup and processing. Production wellheads are complete with all valves required to isolate the production well and collection manifold.

The coal consumption rate at 100% plant factor is 5,753 daf t of coal per day. Allowing for the content in each coal seam results in dry coal consumption rates of 7,366 t/d for the Bowron coalfield and 7,111 t/d for the Tulameen coalfield. The total coal consumed during 20 years of operation at 100% capacity is 53.8 million dry tonnes for the Bowron

coalfield and 52 million dry tonnes for the Tulameen coalfield.

2. Surface Processing Facilities

The surface facilities are located off the coalfield in a position about midway along the known outcrops in both coalfields. This avoids problems with subsidence that may occur above gasified regions and leads to an acceptable layout of piping for the field facility. For the Bowron coalfield, the surface facility is adjacent to the outcrop of the west limb. For the Tulameen coalfield, the facility is located about midway along the northeast outcrop so as to avoid the old mined regions to the south. Alternate similar plant locations could be used with only a minor effect on plant cost, since only the length of piping connecting the surface and field facilities is altered.

The surface facility consists of the following plant section (Sections 1 and 2 are field facilities).

Plant Section	Process Unit
3	heat exchange and gas scrubbing
4	gas compression and CO shift
5	acid gas removal for CO_2 and H_2S; Benfield Hi-Pure process
6	zinc-oxide guard beds and methanization
7	compression and drying
8	fuel gas treating; DEA process
9	sulphur removal; Stretford process
10	raw and waste water treatment
11	oil separation and recovery
12	oxygen plant
13	steam plant

The raw-gas transport piping delivers the gas to the heat exchange and gas scrubbing section of the surface facility (Plant Section 3). Two separate heat-exchange and gas

scrubbing trains are used. The raw gas is first cooled by exchanging heat with the compressed feed gas to the CO-shift reactor. Further cooling is done in a humidifier to condense and remove oils from the gas that are then sent to the oil recovery section (Plant Section 11). The gas exiting the oil/gas separator is sent to a wet scrubber and de-mister for final removal of particulate matter and oils. The bottoms from the scrubber are sent to the oil recovery section. Separated water is recirculated to the scrubber.

Clean gas exiting the wet scrubber is split into two streams, one going to the fuel-gas treating section (Plant Section 8) to satisfy plant fuel requirements, the other becoming make-up gas for SNG production.

Single units of all SNG-processing plant sections are used downstream of the wet scrubber starting with Plant Section 4, gas compression and carbon monoxide shift. The gas is compressed from 330 kPa to 3,100 kPa in three stages with inter-cooling in preparation for CO-shift conversion. The gas exiting the last compressor is heated by heat exchange with the raw product gas from field facilities to a temperature of 285°C. This gas is heated further with the exit gas from the shift unit and mixed with steam before entering the CO-shift reactor. The gas is shifted to a H_2/CO ratio of 3.15.

The gas from the shift unit contains undesired carbon dioxide and hydrogen sulphide. These are removed using the Benfield Hi-Pure process. Prior to the Benfield unit, the gas is used to heat the feed to the methanation unit and to generate low-pressure steam needed in other parts of the plant. Acid gas separated by the Benfield unit is sent to the Stretford plant for separation of sulphur, while the cleaned make-up gas continues on to the methanation section.

The gas enters the methanation section at 2,450 kPa and 270°C and is immediately raised to 340°C before entering a zinc-oxide guard bed. This bed removes the last traces of H_2S to prolong the life of the methanation catalyst.

Methanation is carried out in three, fixed-bed reactors arranged in series. The gas is cooled after the first and second reactors by generating steam and heating boiler feed-water. Control of process yields is achieved by re-cycle of product gas.

The SNG product exiting the final reactor is used to heat the methanation feed gas, then is directed to a compression and drying section. The pressure of the gas is raised from 2,450 kPa to 7,000 kPa and cooled to 38°C for commercial

delivery. The cooling step is the first stage of water removal. Final dehydration is done in a glycol drying unit.

The fuel gas taken off at the exit of the wet scrubber is passed through DEA absorbers to remove hydrogen sulphide. Treated gas is used to generate steam for underground gasification and other plant processes. The separated acid gases, hydrogen sulphide and some carbon dioxide, are sent to the Stretford unit to recover sulphur.

Waste water from the plant is stripped in a steam column and passed through activated-charcoal absorbers.

The oil separation and recovery section of the plant (Plant Section 11) takes contaminated oil separated from the raw product gas in Plant Section 3 and, by vacuum distillation, obtains a partially-purified oil used within the plant for boiler fuel.

Material flow rates for major streams in the surface facility are given in Table 15. Stream numbers refer to Figure 21.

The composition and higher heating value of the SNG product is given in Table 16.

3. Plant Thermal Efficiency

The overall efficiency of the complete plant based on the higher heating values of the coal and SNG product is 30%. This value arises from an efficiency of 51% for the field gasification facility and an efficiency of 59% for the surface processing facility.

D. SYNTHESIS GAS (SYNGAS) PLANT

The same design for the field-gasification facility is used for the synthesis gas plant in each coalfield as described earlier for the synthetic natural gas plant. The coal consumption rate in each case is also identical.

A general schematic of the major process steps in the production of syngas is presented in Figure 23. Numbers shown for process streams apply to data shown later in the discussion of material flows in the surface facility.

1. Field Development Facilities

The syngas plant was sized to consume coal at the same rate as the SNG plant. These rates are 2.69 million dry

Table 15

MATERIAL FLOWS FOR A 1.5 X 10^6 m^3/d SNG PLANT

Stream Number	1	2	3	4	5	6	7	8	9	10	11
Coal Insitu (daf t/d)	5,753										
Coal Gasified (daf t/d)	4,314										
Total Gas (kmol/d)				413,641			413,641				319,292
(m^3/d X 10^3)				9,780			9,780				7,548
(GJ/d)				88,021			88,021				88,021
H_2 (kmol/d)				107,581			107,581				107,581
CO (kmol/d)				107,581			107,581				107,581
CO_2 (kmol/d)				62,132			62,132				62,132
CH_4 (kmol/d)				24,738			24,738				24,738
C_2+ (kmol/d)				2,877			2,877				2,877
H_2S (kmol/d)				1,151			1,151				1,151
H_2O (kmol/d)				107,581			107,581				13,232
Elemental S (t/d)											
O_2 feed (kmol/d)			76,515								
H_2O feed (kmol/d)		76,515									
Temperature (°C)				340			340				66
Pressure (kPa)				500			470				330

Table 15 (continued)

MATERIAL FLOWS FOR A 1.5 X 10^6 m^3/d SNG PLANT

Stream Number		12	13	14	15	16	17	18	19	20	21	22
Coal Insitu (daf t/d)												
Coal Gasified (daf t/d)												
Total Gas	(kmol/d)	86,295	232,997	342,879	93,084	178,343	101,828		63,456	69,036	17,086	
	(m^3/d X 10^3)	2,040	5,508	8,106	2,201	4,216	2,407		1,500	1,632	404	
	(GJ/d)	24,163	63,858	64,434		64,434	54,654		54,654	24,163		
H_2	(kmol/d)	29,053	78,528	119,087		119,087	2,877		2,301	29,053		
CO	(kmol/d)	29,053	78,528	37,970		37,970	57		57	29,053		
CO_2	(kmol/d)	16,799	45,334	85,720	85,547	173	115		115	0	16,799	
CH_4	(kmol/d)	6,904	17,834	17,834		17,834	60,407		60,407	6,904		
C_2+	(kmol/d)	805	2,071	2,071		2,301			0	805		
H_2S	(kmol/d)	288	863	863	863	0			0	0	288	
H_2O	(kmol/d)	3,567	9,665	78,816	6,673	1,151	38,257	38,251	6	3,452		
Elemental S (t/d)												36.9
O_2 feed (kmol/d)												
H_2O feed (kmol/d)												
Temperature (°C)		66	66	121		232	54		38	54	54	
Pressure (kPa)		296	330	2,839		2,784	2,412		7,076	269	138	

Table 16

COMPOSITION AND HEATING VALUE OF SNG

Constituent	Vol %
H_2	3.6
CO	0.1
CO_2	0.2
CH_4	95.2
H_2O	0.01
N_2	1.0 (assumed)

Higher Heating Values: 36.3 MJ/m^3 @ 15°C

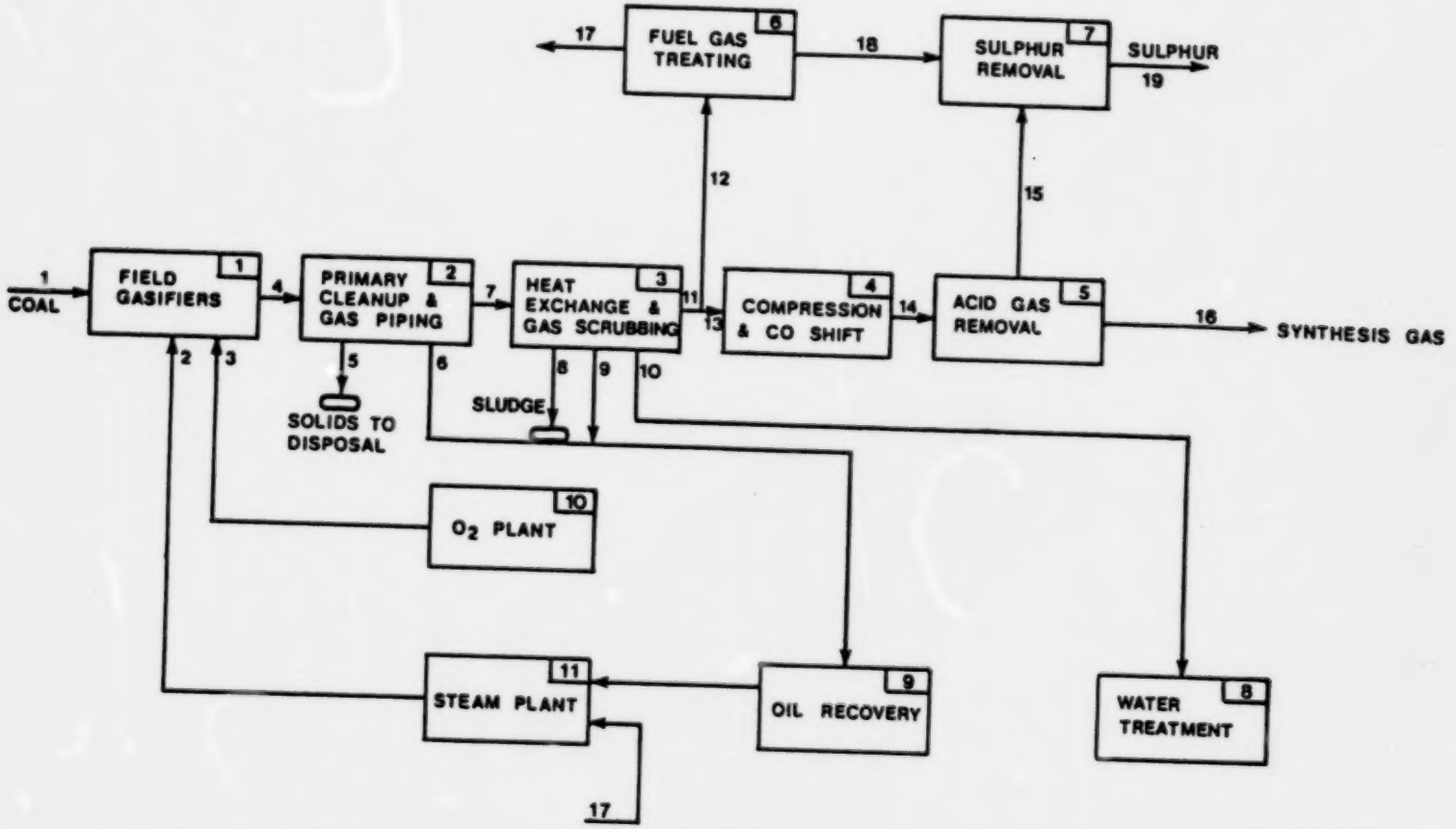


FIGURE 23 SYNTHESIS GAS PLANT

tonnes per year for the Bowron coalfield and 2.60 million dry tonnes per year for the Tulameen coalfield; these values differ slightly as a consequence of the different ash contents of the coal in each coalfield.

The design of the field facility for the syngas plant is identical to that of the SNG plant and is not repeated here.

2. Surface Processing Facilities

The surface facility in the Bowron coalfield is located midway along the outcrop of the west limb, while it is located midway along the northeast outcrop in the Tulameen coalfield. These are the same locations that were used for the SNG plant. The facilities were not placed on the coalfield to avoid problems with subsidence and to maximize the resource that could be recovered.

The surface facility consists of the following plant sections (Sections 1 and 2 are field facilities).

Plant Section	Process Unit
3	heat exchange and gas scrubbing
4	gas compression and CO shift
5	acid gas removal for CO_2 and H_2S; Benfield Hi-Pure process
6	fuel gas treating; DEA process
7	sulphur removal; Stretford process
8	raw and waste water treatment
9	oil separation and recovery
10	oxygen plant
11	steam plant

The elements of the surface facility are identical to the SNG plant, except for the absence of the methanation, compression, and drying units.

Raw gas from the field facility is received at the heat-exchange and gas-scrubbing section for processing to yield an oil and particulate matter free gas suitable for CO shift.

Twin, gas-cleanup trains are used; one for each gasifier train.

The stream exiting the wet scrubber is split into two streams; one for use as fuel within the plant, the other for processing to syngas. The fuel stream is sent to a single, fuel gas treating unit to remove hydrogen sulphide prior to combustion in the plant steam boiler. The make-up gas stream is compressed and sent to the CO-shift reactor to yield a gas with a H_2:CO ratio of 2:1. Single units of all plant sections are used downstream of the gas-scrubbing section.

Following the shift reactor, the gas is sent to a Benfield Hi-Pure plant to remove hydrogen sulphide and carbon dioxide. These acid gases are sent to a Stretford plant to recover sulphur for sale.

Following the Benfield plant, the synthesis gas is cooled to 38°C and left at the exit pressure of 2,790 kPa for commercial delivery.

The fuel gas taken off at the exit of the wet scrubbers is passed through DEA absorbers for removal of hydrogen sulphide. Treated gas is sent to the steam plant for generation of steam for underground gasification and other plant uses such as turbocompressors. Separated acid gases are sent to the Stretford unit for recovery of sulphur.

Waste water, containing oils and suspended solids, is sent to the waste water treatment section for steam stripping and charcoal absorption.

Oil separated from the raw gasification product gas is purified in the oil-recovery section to yield a fuel oil suitable for use in the steam boiler.

An abbreviated material balance for the plant is given in Table 17 showing the flow rates of major flow streams. The stream numbers are identified in Figure 23.

The composition and higher heating value of the syngas is given in Table 18.

3. Plant Thermal Efficiency

The overall efficiency of the complete plant based on the higher heating values of the coal in place and the syngas product is 32%. This value is the product of an efficiency of 51% for the underground gasification facility and an efficiency of 63% for the surface processing facility.

Table 17

MATERIAL FLOWS FOR A 3.8 X 10^6 m^3/d SYNGAS PLANT

Stream Number	1	2	3	4	5	6	7	8	9	10	11
Coal Insitu (daf t/d)	5,753										
Coal Gasified (daf t/d)	4,314										
Total Gas (kmol/d)				413,641			413,641				319,292
(m^3/d X 10^3)				9,780			9,780				7,548
(GJ/d)				88,021			88,021				88,021
H_2 (kmol/d)				107,581			107,581				107,581
CO (kmol/d)				107,581			107,581				107,581
CO_2 (kmol/d)				62,132			62,132				62,132
CH_4 (kmol/d)				24,738			24,738				24,738
C_2^+ (kmol/d)				2,877			2,877				2,877
H_2S (kmol/d)				1,151			1,151				1,151
H_2O (kmol/d)				107,581			107,581				13,232
Elemental S (t/d)											
O_2 feed (kmol/d)			76,515								
H_2O feed (kmol/d)		76,515									
Temperature (°C)				340			340				66
Pressure (kPa)				500			470				330

Table 17 (continued)

MATERIAL FLOWS FOR A 3.8 X 10^6 m^3/d SYNGAS PLANT

Stream Number		12	13	14	15	16	17	18	19
Coal Insitu (daf t/d)									
Coal Gasified (daf t/d)									
Total Gas	(kmol/d)	109,882	209,409	306,232	64,836	159,531	88,251	21,861	
	(m^3/d X 10^3)	2,598	4,950	7,239	1,533	3,800	2,086	517	
	(GJ/d)	30,491	57,530	57,530		57,472	30,491		
H_2	(kmol/d)	37,107	70,474	94,062		94,062	37,107		
CO	(kmol/d)	37,107	70,474	46,887		46,887	37,107		
CO_2	(kmol/d)	21,459	40,674	64,261	64,088	173	0	21,459	
CH_4	(kmol/d)	8,514	16,223	16,166		16,166	8,514		
C_2^+	(kmol/d)	978	1,898	1,898		1,898	978		
H_2S	(kmol/d)	403	748	748	748	0	0		
H_2O	(kmol/d)	4,545	8,687	82,153		345	4,545		
Elemental S (t/d)									36.9
O_2 feed (kmol/d)									
H_2O feed (kmol/d)									
Temperature (°C)		66	66	121		38	54	54	
Pressure (kPa)		296	330	2,839		2,790	269	138	

Table 18

COMPOSITION AND HEATING VALUE OF SYNGAS

Constituent	Vol %
H_2	58.4
CO	29.2
CO_2	0.1
CH_4	10.0
H_2O	0.2
N_2	1.0

Higher Heating Values: 15.1 MJ/m^3 @ 15°C

VII. CAPITAL INVESTMENTS

A. METHODS OF COSTING AND SOURCES OF DATA

Costs for drilling and completion of injection and production wells were derived from data presented in a report by Williams Bros. Engineering Co. The cost factors used for estimating are $311/m for 500-metre completed, inclined production wells and $170/m for completed vertical wells.

Costs for surface facilities are based on cost data presented in reports by Ulrich et al (1979 a, b) of Oak Ridge National Labs. Cost data contained in reports by Pritchard Corporation (1980) were used for comparison purposes. Final plant costs were compared to results given by Whitman et al for syngas production and to results given by Bruggink et al for SNG production.

All capital costs were updated to mid-1982 dollars using the CE Plant Cost Index for Equipment and Machinery published by Chemical Engineering.

Capital costs were scaled to required capacities using the power law with exponents tabulated by Guthrie and Humpreys and Katell.

Factored estimates were used for engineering construction overhead, contingency, contractors' fee, and corporate overhead. Special charges cover costs for licensing processes, royalties, freight, and taxes.

B. SYNTHETIC NATURAL GAS PLANT

Table 19 itemizes capital investment for the Bowron coalfield SNG plant.

Site development covers the cost of sanitary and process sewer systems, storm drainage, fencing, roads and parking lots, waste water evaporation ponds, and a railway line running within the plant. The cost of a railway to the plant and costs of utility services outside the plant gate are excluded.

Coalfield characterization includes the cost of an initial geological and hydrogeological characterization of the coalfield. It is assumed that a total of 9,000 m of drilled hole is used for this characterization at a cost of $128/m. Associated engineering and analysis of the data is added to the drilling cost.

Process wells have to be drilled during the construction phase in preparation for startup. It was assumed that one half of the

Table 19

CAPITAL INVESTMENT FOR THE BOWRON COALFIELD SNG PLANT

Item	$ X 10^6
site developement	1.500
coalfield characterization	1.404
field gas treating	6.904
field piping	9.192
raw gas treating	11.859
CO shift	20.144
oxygen plant	64.788
Benfield plant	14.516
methanation plant	19.961
fuel gas treating	5.521
Stretford plant	3.616
waste water treatment and oil recovery	4.389
utilities and off-sites	29.255
capitalized drilling cost	9.633
engineering	9.582
construction overhead and startup	18.206
contingency	32.915
contractors' fee	6.583
special charges	13.000
corporate overhead	19.165
Total Depreciable Capital Investment	302.133
land and coal rights	13.000
working capital	18.128
Total Capital Investment	333.261

normal annual requirement of wells would be pre-drilled during construction. This initial drilling was capitalized.

The cost factors for estimation of the engineering and construction of the plant are given in Appendix B.

The cost of purchasing the land, coal rights, and outstanding royalty agreements is given in Table 19 as the cost of Land and Coal Rights. The value of $13 million is the average of a very rough estimate of the range of these costs made by Dolmage Campbell & Assoc. These costs varied from $5 to $20 million, depending on the assumptions made for the estimate.

Table 20 itemizes capital investment for the SNG plant at the Tulameen coalfield. All costs of plant sections are identical to those for the Bowron coalfield. Differences in the capital cost arise because of the greater thickness of the Main seam of the Tulameen coalfield and the resulting decrease in the number of wells which must be drilled during the construction phase. This affects the depreciable capital cost and the working capital requirement.

The estimate of the cost of the land and coal rights ranged from $5 to $10 million. An average value of $8 million was chosen as the base case.

C. SYNTHESIS GAS PLANT

Table 21 itemizes capital investment for the syngas plant at the Bowron coalfield.

Capital costs for site development, coalfield characterization, and many of the plant sections are similar to or the same as for the SNG plant.

Capital investment for the syngas plant at the Tulameen coalfield is given in Table 22.

Table 20

CAPITAL INVESTMENT FOR THE TULAMEEN COALFIELD SNG PLANT

Item	$ X 10^6
site developement	1.500
coalfield characterization	1.404
field gas treating	6.904
field piping	9.192
raw gas treating	11.859
CO shift	20.144
oxygen plant	64.788
Benfield plant	14.516
methanation plant	19.961
fuel gas treating	5.521
Stretford plant	3.616
waste water treatment and oil recovery	4.389
utilities and off-sites	29.255
capitalized drilling cost	4.103
engineering	9.582
construction overhead and startup	18.206
contingency	32.915
contractors' fee	6.583
special charges	13.000
corporate overhead	19.165
Total Depreciable Capital Investment	296.603
land and coal rights	9.000
working capital	17.796
Total Capital Investment	322.399

Table 21

CAPITAL INVESTMENT FOR THE BOWRON COALFIELD SYNGAS PLANT

Item	$ X 10^6
site developement	1.500
coalfield characterization	1.404
field gas treating	6.904
field piping	9.192
raw gas treating	12.227
CO shift	18.417
oxygen plant	64.788
Benfield plant	11.606
fuel gas treating	6.447
Stretford plant	3.616
waste water treatment and oil recovery	4.389
utilities and off-sites	29.255
capitalized drilling cost	9.633
engineering	8.417
construction overhead and startup	15.992
contingency	28.913
contractors' fee	5.783
special charges	11.000
corporate overhead	16.834
Total Depreciable Capital Investment	266.317
land and coal rights	13.000
working capital	15.979
Total Capital Investment	295.296

Table 22

CAPITAL INVESTMENT FOR THE TULAMEEN COALFIELD SYNGAS PLANT

Item	$ X 10^6
site developement	1.500
coalfield characterization	1.404
field gas treating	6.904
field piping	9.192
raw gas treating	12.227
CO shift	18.417
oxygen plant	64.788
Benfield plant	11.606
fuel gas treating	6.447
Stretford plant	3.616
waste water treatment and oil recovery	4.389
utilities and off-sites	29.255
capitalized drilling cost	4.103
engineering	8.417
construction overhead and startup	15.992
contingency	28.913
contractors' fee	5.783
special charges	11.000
corporate overhead	16.834
Total Depreciable Capital Investment	260.787
land and coal rights	8.000
working capital	15.647
Total Capital Investment	284.434

VIII. OPERATING COSTS

Operating costs included in this section exclude interest on debt, return on equity, and capital depreciation.

The following operating costs are included:

proportional expenses:
- coal;
- catalysts and chemicals;
- raw water;
- drilling of process wells;
- movement of field piping;

constant expenses:
- operating labour;
- labour burden;
- supervisory labour;
- operating supplies;
- general administration and overhead;
- maintenance materials and labour;
- taxes and insurance.

Constant expenses are those which are relatively insensitive to the plant capacity factor. For estimating purposes, the remaining expenses are assumed to be directly proportional to the plant capacity factor. Estimates are given in this report for proportional expenses at 100% capacity. These are adjusted automatically during the computation of product prices to suit actual plant factors.

The annual cost of maintenance, labour burden, supervision, operating supplies, and overhead are based on factored estimates using either depreciable capital investment or operating labour as a base. The assumptions for these estimates are summarized in Appendix B.

Taxes and insurance costs were estimated as a fraction of total capital investment at the time of plant startup:

taxes: 1% of total capital investment;

insurance: 1.5% of total capital investment.

These values are not tabulated with other operating costs to avoid confusion, since these costs begin at the time of plant startup and, therefore, depend on the inflation rate.

Although coal is included as a proportional expense, no charge was actually assigned to the coal since the land and coal rights were purchased at the start of construction.

The cost of general administration and overhead includes a corporate overhead of 20% of labour plus supervision. Costs of

marketing and distribution to arrive at a final delivered product price are not included. Predicted product prices are, therefore, plant-gate prices.

A. SYNTHETIC NATURAL GAS PLANT

Table 23 presents a detailed summary of operating requirements and operating costs for the Bowron and Tulameen coalfields. Drilling costs are presented according to the number of wells drilled during the year, which varies in the first and last years of operation.

B. SYNTHESIS GAS PLANT

Table 24 itemizes operating costs for the syngas plants in the Bowron and Tulameen coalfields.

Table 23

OPERATING COSTS FOR A SNG PLANT AT THE BOWRON AND TULAMEEN COALFIELDS

		Bowron Coalfield		Tulameen Coalfield	
	Unit Price Basis	Quantity	Annual Cost ($ X 10^6)	Quantity	Annual Cost ($ X 10^6)
Constant Expenses:					
operating labour	$13.50/hour	24 men/shift	2.696	24 men/shift	2.696
labour burden	35% op. labour		0.944		0.944
supervision	15% op. labour and labour burden		0.546		0.546
operating supplies	30% op. labour		0.809		0.809
general administration and overhead	135% op. labour and supervision		4.377		4.377
maintenance material and labour	4% depreciable capital		12.085		11.864
			21.457		21.236
Proportional Expenses (100% plant factor):					
coal	0	2.69 Mt/yr	--	2.60 Mt/yr	--
catalysts and chemicals			2.295		2.295
raw water	$0.11/kl	3.68 X 10^6 kl/yr	0.405	3.68 X 10^6 kl/yr	0.405
drilling					
vertical wells	$170/m	369/185	12.546/6.273	102/51	4.162/2.081[a]
inclined wells	$311/m	43/22	6.687/3.343	13/11/0	2.022/1.711/0[b]
field moves			1.750		0.461
			23.683/14.066		9.345/9.034/5.242
Total Operating Costs			45.140/35.523		30.581/30.270/26.478

[a] First year through nineteenth operating year/twentieth operating year.

[b] First operating year/second through nineteenth operating year/twentieth operating year.

Table 24

OPERATING COSTS FOR A SYNGAS PLANT AT THE BOWRON AND TULAMEEN COALFIELDS

		Bowron Coalfield		Tulameen Coalfield	
	Unit Price/Basis	Quantity	Annual Cost ($ X 10^6)	Quantity	Annual Cost ($ X 10^6)
Constant Expenses:					
operating labour	$13.50/hour	22 men/shift	2.471	22 men/shift	2.471
labour burden	35% op. labour		0.865		0.865
supervision	15% op. labour and labour burden		0.500		0.500
operating supplies	30% op. labour		0.741		0.741
general administration and overhead	135% op. labour and supervision		4.011		4.011
maintenance material and labour	4% depreciable capital		10.653		10.431
			19.241		19.019
Proportional Expenses (100% plant factor):					
coal	0	2.69 Mt/yr	--	2.60 Mt/yr	--
catalysts and chemicals					
raw water	$0.11/kl	3.57 X 10^6 kl/yr		3.57 X 10^6 kl/yr	
drilling					
vertical wells	$170/m	369/185	12.546/6.273	102/51	4.162/2.081[a]
inclined wells	$311/m	43/22	6.687/3.343	13/11/0	2.022/1.711/0[b]
field moves			1.750		0.461
			22.276/12.659		7.938/7.627/3.835
Total Operating Costs			41.517/31.900		26.957/26.646/22.854

[a] First year through nineteenth operating year/twentieth operating year.

[b] First operating year/second through nineteenth operating year/twentieth operating year.

IX. FINANCIAL ANALYSIS

This chapter utilizes capital investment requirements covered in Chapter VII and operating costs covered in Chapter VIII to predict plant-gate product prices for synthetic natural gas and syngas. Product prices are predicted for both the Bowron and Tulameen coalfields for a set of capital costs, operating costs, and financial parameters termed to be the "base case". The sensitivity of the product prices to the input parameters is investigated for those parameters that are subject to significant error or to changing economic conditions.

A. CASES STUDIED

The plant types and locations considered in the financial analysis are as follows.

Plant Location	Primary Product		Byproduct	
	Type	Rate	Type	Rate
Bowron Coalfield	SNG	1.5 X 10^6 m^3/d	Sulphur	36.9 t/d
	Syngas	3.8 X 10^6 m^3/d	Sulphur	36.9 t/d
Tulameen Coalfield	SNG	1.5 X 10^6 m^3/d	Sulphur	36.9 t/d
	Syngas	3.8 X 10^6 m^3/d	Sulphur	36.9 t/d

B. CAPITAL AND OPERATING COSTS

Capital and operating costs determined in Chapters VII and VIII were in mid-1982 dollars. These costs were inflated to January, 1983 dollars using a 3.5% inflation factor. A summary of the costs input to the financial analysis is given below. Indicated operating costs exclude taxes, insurance, and feedstock costs.

Plant Location	Product	Total Capital Investment (Jan.1983 $ X 10^6)	Operating Cost (Jan.1983 $ X 10^6)	
			Constant	Proportional
Bowron Coalfield	SNG	344.925	22.208	24.512/14.558[a]
	Syngas	305.631	19.914	23.056/13.102
Tulameen Coalfield	SNG	333.683	21.979	9.672/9.350/5.425[b]
	Syngas	294.389	19.685	8.216/7.894/3.969

[a] First through nineteenth operating year/twentieth operating year.

[b] First operating year/second through nineteenth operating year/ twentieth operating year.

Capital and operating costs are inflated within the financial computer model to apply to the year in which they occur. The economic parameters controlling the inflation of the costs to the year in which they occur are defined in the following section. All costs were assumed to increase at the rate of inflation.

C. ECONOMIC PARAMETERS

The economic parameters used for the analysis of the base case plants are summarized in Appendix B. For convenience, the more important parameters are repeated in Table 25.

An inflation rate of 7% per year was assumed to apply over the full life of plant. This value is 0.5% less than the value estimated by B.C. Hydro in the report "Long-Term Economic Outlook, 1982 - 2001" for 1987 to 2001. The assumed interest rate on debt of 11% was set at 4% over the inflation rate as suggested by Mr. J. Cawdery of B.C. Hydro.

Interest charges during construction are added annually to long-term debt. Interest rate during construction is the same as for long-term debt during the operation period.

Since the B.C. mining tax does not apply to B.C. Hydro, no charge is made for coal consumed by the plant outside of the capital cost for the initial purchase of land and coal rights.

Byproduct sulphur is sold at a price of $70/t. This price is $5/t less than the molten sulphur price as of November 1982, free-on-board tank cars in Alberta. Sulphur sales add to total plant revenue.

D. FINANCIAL ANALYSIS FOR BASE CASES

A computer model was used that develops a cash flow table over the life of the plant. The model determines a January 1983, levelized product price that pays back debt principle and interest, covers all operating costs, and decreases the outstanding capital to zero at the end of the plant operating life. In the final operating year, outstanding capital at the end of the year equals working capital, which is recovered intact.

The plant is assumed to function independently. Consequently, no negative cash flows are transferred to a parent company.

Table 26 summarizes product prices determined for base case conditions. It is evident from these results that the Tulameen coalfield is a preferable location for the SNG and syngas plants. A major reason for the lower product price at the Tulameen

Table 25

ABBREVIATED LIST OF ECONOMIC PARAMETERS FOR BASE CASE ANALYSIS

1.	Period of Analysis	1983 - 2005 3-year construction period 20-year operating life
2.	Schedule of Capital Spending During Construction	1983 10% 1984 40% 1985 50%
3.	Plant Capacity Factor	1986 50% 1987 - 2005 90%
4.	Long-Term Debt-Interest Rate	11%
5.	Source of Financing	100% debt
6.	Depreciation	Land and working capital not depreciable. Straight-line depreciation over 20-year operating life.
7.	Inflation Rate	All costs and revenue inflate at 7% per year.
8.	Income Taxes	None
9.	Salvage Values of Plant and Land	Nil
10.	Timing of Costs	Investments made at start of year. Operating expenses paid at end of year.
11.	Working Capital	Working capital recovered intact at end of operating life.

Table 26

PRODUCT PRICES FOR SNG AND SYNGAS UNDER BASE CASE CONDITIONS

Product	Plant Location	Product Price	
		Jan.1983 $/GJ	Jan.1983 $/km^3
SNG	Bowron Coalfield	4.19	152.10
	Tulameen Coalfield	3.37	122.33
Syngas	Bowron Coalfield	3.58	54.06
	Tulameen Coalfield	2.81	42.43

coalfield is the much lower operating cost resulting from the greater thickness of the coal seam.

Payout tabulations are given in Tables B-2 to B-5 in Appendix B for the base case analysis.

E. SENSITIVITY ANALYSIS

The sensitivity of the product price to many of the financial parameters and costs was investigated. The factors studied in this sensitivity analysis include:

- capital cost ± 20%;
- proportional operating cost ± 20%;
- constant operating cost ± 20%;
- 50% increase in the cost of land and coal rights;
- decrease in the plant factor from 0.9 to 0.8;
- 20% increase in working capital;
- increase in the real interest rate from 4% to 6%;
- increase in the inflation rate from 7% to 9%;
- decrease in the inflation rate to zero with debt interest at 11%;
- increasing total drilling cost as depth of gasification increases during the plant operating life.

For the Tulameen coalfield only, the effect of a 40% increase in capital cost was also determined.

The results of the sensitivity analysis for SNG and syngas products are given in Tables 27 and 28.

A 50% increase in the cost of land and coal rights, which brings the cost of this item to the top of the range estimated originally, has a minor affect on product price for both coalfields. The sensitivity of the product price to this cost is higher for the Bowron coalfield than for the Tulameen coalfield, as would be expected because of its higher absolute cost; the base case costs were $\$13 \times 10^6$ and $\$8 \times 10^6$ for the Bowron and Tulameen coalfields, respectively.

Increasing the inflation rate from 7% to 9%, while keeping all other parameters constant including the real interest rate of 4%, has a small effect on product price. Product prices decreased slightly when raising the inflation rate 2% because of the effect of inflation on revenue.

The greatest change of product price occurred when the inflation rate was reduced to zero while maintaining debt interest at 11%. This is an extreme case and is included to indicate an upper bound to the product prices expected for the two coalfields,

Table 27

SENSITIVITY ANALYSIS FOR SNG

	Bowron Coalfield Product Price (Jan.1981 $/GJ)			Tulameen Coalfield Product Price (Jan.1981 $/GJ)		
	Base Case	Sensitivity Case	Change	Base Case	Sensitivity Case	Change
Capital Cost, + 20%	4.19	4.51	+ 7.6%	3.37	3.68	+ 9.2%
Capital Cost, + 40%				3.37	4.00	+18.7%
Capital Cost, - 20%	4.19	3.86	- 7.8%	3.37	3.05	- 9.5%
Proportional Operating Cost, + 20%	4.19	4.43	+ 5.7%	3.37	3.46	+ 2.7%
Proportional Operating Cost, - 20%	4.19	3.94	- 6.0%	3.37	3.27	+ 3.0%
Constant Operating Cost, + 20%	4.19	4.44	+ 6.0%	3.37	3.62	+ 7.4%
Constant Operating Cost, - 20%	4.19	3.93	- 6.2%	3.37	3.11	- 7.7%
Land and Coal Rights, + 50%	4.19	4.22	+ 0.7%	3.37	3.38	+ 0.3%
Plant Factor Decreased to 0.8	4.19	4.55	+ 8.6%	3.37	3.72	+10.4%
Working Capital, + 20%	4.19	--	--	3.37	3.38	+ 0.3%
Real Debt Interest Rate 6%	4.19	4.53	+ 8.1%	3.37	3.70	+ 9.8%
Inflation Rate 9%, Debt at 13%	4.19	4.14	- 1.2%	3.37	3.32	- 1.5%
Inflation Rate 0%, Debt at 11%	4.19	5.94	+42%	3.37	5.06	+50%
Increased Drilling Cost	4.19	5.29	+26.3%	3.37	3.47	+ 3.0%

Table 28

SENSITIVITY ANALYSIS FOR SYNGAS

	Bowron Coalfield Product Price (Jan.1981 $/GJ)			Tulameen Coalfield Product Price (Jan.1981 $/GJ)		
	Base Case	Sensitivity Case	Change	Base Case	Sensitivity Case	Change
Capital Cost, + 20%	3.58	3.83	+ 7.0%	2.81	3.07	+ 9.3%
Capital Cost, + 40%				2.81	3.33	+18.5%
Capital Cost, - 20%	3.58	3.31	- 7.5%	2.81	2.54	- 9.6%
Proportional Operating Cost, + 20%	3.58	3.80	+ 6.2%	2.81	2.88	+ 2.5%
Proportional Operating Cost, - 20%	3.58	3.36	- 6.2%	2.81	2.73	- 2.9%
Constant Operating Cost, + 20%	3.58	3.80	+ 6.2%	2.81	3.02	+ 7.5%
Constant Operating Cost, - 20%	3.58	3.36	- 6.2%	2.81	2.59	- 7.8%
Land and Coal Rights, + 50%	3.58	3.61	+ 0.8%	2.81	2.82	+ 0.3%
Plant Factor Decreased to 0.8	3.58	3.88	+ 8.4%	2.81	3.10	+10.3%
Working Capital, + 20%	3.58	3.59	+ 0.3%	2.81	2.82	+ 0.3%
Real Debt Interest Rate 6%	3.58	3.87	+ 8.1%	2.81	3.08	+ 9.6%
Inflation Rate 9%, Debt at 13%	3.58	3.54	- 1.1%	2.81	2.77	- 1.4%
Inflation Rate 0%, Debt at 11%	3.58	5.05	+41.1%	2.81	4.22	+50%
Increased Drilling Cost	3.58	4.63	+29.3%	2.81	2.90	+ 3.2%

and to emphasize the importance of including inflation in the analysis.

One of the assumptions made in developing costs for the base case plants was that the cost per completed well remained relatively constant during the life of the plant. The drilling costs that were used apply to single wells and are, consequently, much higher than would apply for drilling of a large number of wells on a regular basis as would be the case for the gasification plant. The drilling costs per well were based on a drilled length of 500 m for the inclined hole; this distance also dictated the depth of attendant vertical wells. An inclined well of this length has a vertical depth of near 300 m in both coal seams, neglecting the difference in seam dip. Since there is insufficient coal at depths less than 300 m in both coalfields to supply the plant for 20 years, deeper coals must be gasified, and, consequently, deeper wells than those assumed are needed. For the base case, the assumed constancy of the cost of completed wells attempts to account, in a simple way, for the reduction in well costs that would result during the operating life of the plant because of economies of scale and the familiarity of operators with the geological characteristics of the coalfield. This assumption leads to an optimistic product price.

Because drilling cost is a major part of the total proportional operating cost and the fact that increasingly deeper coals would have to be gasified in the coalfield, a product price was determined assuming there was no reduction in cost per metre of drilled wells and that the depth of gasification increased as the identified reserves were exhausted. The length of the inclined portion of the production well in the seam was kept at 500 m, resulting in access to coal in depth increments of 300 m. These wells were assumed to be drilled directionally starting from the vertical and to be cased to point of entry in the seam.

Table 29 summarizes the drilling costs by year for the coalfields. Costs increase more quickly for the Bowron coalfield because less coal resides at depths less than 300 m. Use of the costs for the Bowron coalfield results in a substantial increase of SNG and syngas prices (Tables 27 and 28). The effects of the increases in drilling cost are quite small for the Tulameen coalfield, since much more coal is available at depths less than 300 m.

The assumption made for the estimate of drilling cost for the base case may be overly optimistic for the Bowron coalfield, since coal reserves at depths greater than 600 m must be gasified. On the other hand, the drilling costs assumed for the sensitivity case are believed to be pessimistic. Actual product prices for the Bowron coalfield are expected to fall between these two extremes, the mean being $4.74/GJ for SNG and $4.10/GJ for syngas.

Table 29

DRILLING COSTS AS DEPTH OF GASIFICATION INCREASES
(Costs Used for Sensitivity Analysis)

Year:	1-5	6-12	13-19	20
Coal Depth (m):	100-300	300-600	> 600	> 600
Bowron Coalfield				
Drilling Cost (mid-1982 $ X 10^6)				
Vertical Wells	12.546	28.229	43.911	22.026
Inclined Wells	6.687	12.694	17.957	9.187
	19.233	40.923	61.868	31.202

Year:	1	2-10	11-19	20
Coal Depth (m):	100-300	100-300	300-600	300-600
Tulameen Coalfield				
Drilling Cost (mid-1982 $ X 10^6)				
Vertical Wells	4.162	4.162	7.803	3.902
Inclined Wells	2.022	1.711	3.022	0
	6.184	5.873	10.825	3.902

The insensitivity of the product prices for the Tulameen coalfield to drilling costs is advantageous. Product prices for the optimistic and pessimistic cases are within only about 3% for both SNG and Syngas.

X. OUTLINE OF ACTIVITIES REQUIRED FOR COMMERCIAL DEVELOPMENT OF UNDERGROUND COAL GASIFICATION

To commercialize underground coal gasification requires an integrated program of paper studies, laboratory experimentation, and field trials. The studies are required to benefit from experience and knowledge of other developers, and to assist in the definition of directions to follow in any laboratory and field experimentation.

The following sections give an outline of the future work needed to further the development of gasification technology to a point where a prototype plant can be operated. Only the major targets of future work are considered.

A. FUTURE STUDIES

Many studies of underground coal gasification have been conducted in the United States as part of the development program of the Department of Energy. For example, several studies have led to the development of computer process models for prediction of gas composition, water influx rate, and coal recovery efficiencies. Other work has been done to translate and analyze all available Soviet reports on underground coal gasification to benefit from their field experiences. The environmental impact of the process due to migration of contaminants from the gasified areas and due to subsidence have also been investigated.

Development of underground gasification technology in British Columbia can benefit from the existing information data base available from past work in Alberta, the United States, and in several European countries. The availability of this information substantially reduces the requirement for further studies, although there are needs for studies that relate past experience to the specific case of the prime gasification candidate, the Tulameen coalfield.

Studies on the following subjects are required to pursue the use of underground gasification technology in the Tulameen coalfield:

- migration of chemical groundwater contaminants from the gasified region;
- subsurface and surface subsidence and its potential impact on regional groundwater flow surrounding the coalfield;
- gas composition and reactor growth during gasification as predicted by state-of-the-art process models;
- development work needed to improve directionally drilling capabilities in coal seams;

- capital and operating costs of a plant in the Tulameen coalfield, based on detailed plant analysis;

- impact of SNG or syngas production from the Tulameen coalfield on the social and economic development of the area and on the provincial economy.

A study of the migration of chemical contaminants from a gasified region is needed for the Tulameen coalfield to ensure problems with water use would not occur. Such a study must define the regional hydrogeology near the coalfield and model the release of contaminants that may occur. Data for the types and quantities of contaminants evolved by gasification are available from several short-term field tests. Unfortunately, it is difficult to extrapolate these data to a commercial-scale plant.

Since subsidence alters the behavior of aquifers overlying a gasified region, a study of the effect of subsidence on regional hydrogeology is suggested. The objective of this work would be to ascertain if gasification of the coalfield would result in a major change in the hydrogeology of the area and, possibly, alter the supply of groundwater in other areas.

Prior to any field testing activities, it is important to make full use of computer process models. These models enable investigation of the effects of various site characteristics and operating conditions and, thereby, assist in the design of laboratory and field experiments. Computer process models have been developed to a high level of sophistication at the University of Wyoming at Laramie, at the Lawrence Livermore Laboratory, Livermore, CA, and several other governmental research facilities and private companies.

It is suggested that use be made of the available process models to refine the estimates used in this study for product-gas composition, product-gas yield, and other performance characteristics. Some development work may be needed to tailor the available models to suit the site characteristics of the Tulameen coalfield.

A detailed investigation of technology suitable for the deep, bituminous coal seams present in the Eastern United States was done by Williams Bros. Engineering Co. This study included a survey of drilling technology that details current capabilities for directional drilling in coal seams. Developments by drilling companies are underway to improve the guidance and control of directionally-drilled holes. Because of the importance of directional drilling to the successful development of underground gasification, a study of directional-drilling technology in Canada is needed. This work would ascertain if adequate technology is available or, if not, what the direction of future development of drilling equipment should be to satisfy the needs of underground gasification.

This study developed capital and operating costs based on published cost factors. A more detailed estimate of the costs appropriate to a plant in the Tulameen coalfield would refine the predictions of product price. This work is of less importance at this time than others suggested in this section, since there is presently too much uncertainty in the expected performance of the gasification process. The studies suggested in this and later sections would reduce these uncertainties.

This study considered only the product cost aspects of underground gasification. To put the process in perspective, a study of the impact of the development of underground gasification in the Tulameen coalfield on the local and provincial economies should be conducted.

B. LABORATORY EXPERIMENTS

Laboratory experiments are needed to compliment process modeling efforts and field trials. To avoid some of the expense of field activities, it is suggested that laboratory-scale gasification experiments be conducted with a gasification reactor designed to simulate the growth of the gasification zone in the coal seam. Experiments should also be undertaken to supply fundamental data for the pyrolysis, gasification, and combustion characteristics of the coal in the Tulameen coalfield. These data are required for computer process modeling activities.

Specific targets for any laboratory experiments are:

- determination of the growth of the gasification zone about a borehole in a coal seam having the orientation and quality of the Tulameen Main seam;
- determination of the product gas yield and quality as a function of oxygen and steam injection conditions;
- determination of effect of the swelling behavior of the coal from the Tulameen coalfield.

C. FIELD TRIALS

Upon completion of significant programs of computer process modeling and laboratory simulation, a series of field trials are needed before development of a prototype plant. It is suggested that at least four trials be conducted, each increasing in scale of operation.

Before undertaking any field testing, a thorough characterization study must be conducted to define the geology and hydrogeology

of the site to be used in the test program. The paramount importance of a thorough site characterization to the success of testing activities has been emphasized repeatedly by developers that have conducted field tests in Canada and the United States. The budget cost of characterizing a test site is $500,000, which includes a comprehensive hydrogeological test, definition of site geology, cores of boreholes, engineering, and reporting.

An outline of field trials follows.

Trial 1: A short-term, near-surface test of gasification with oxygen and steam using an inclined production well and a vertical injection well. This test will give experience with drilling and completion of process wells, growth of the gasification zone, and product gas composition and yield. The duration of the test should be about 5 days.

The results of this test will determine whether further testing and development in the coalfield is technically justified and also supply data to enable a more confident estimate of the commercial viability of underground gasification in the coalfield.

Budget Cost: $500,000

Trial 2: A test at the depth planned for commercial operation using an inclined production well and a vertical injection well. This test will expand the data base to improve the data for production gas composition and yield, water influx, and subsidence. The duration of the test should be 30 days.

Budget Cost: $3,000,000

Trial 3: A test physically near Trial 2 using a similar well layout and intended to study environmental issues and investigate methods of improving gasifier control.

Budget Cost: $2,500,000

Trial 4: This is the largest test of the series and would involve simultaneous operation of gasifiers side-by-side at the spacing planned for the commercial plant. All matters of gasifier operation would be studied.

Budget Cost: $4,000,000

The estimated time period required for the series of field trials is about 6 to 10 years, depending on the success level of each field trial.

XI. CONCLUSIONS AND RECOMMENDATIONS

1. Considering both the technical suitability of the Bowron and Tulameen coalfields and the product prices predicted by the financial analysis, the Tulameen coalfield is the most attractive site for underground coal gasification. Some of the positive features of this coalfield are:

   - the resource present is adequate for either an SNG or syngas plant exceeding the plant sizes considered in this study;
   - all the coal needed for the plant operation is present at depths less than 600 m and a dip greater than 30°; deeper coals would have to be used in the Bowron coalfield;
   - within the scope of this work there appears to be few environmental problems associated with gasification in the coalfield, though the potential for contamination of potable aquifers along with other environmental effects of the process would have to be studied to confirm this;
   - the price of SNG ($3.37/GJ) and syngas ($2.81/GJ) produced from the Tulameen coalfield is substantially less than that for the Bowron coalfield;
   - the Steeply Dipping Bed process can be used in the coalfield throughout the plant life.

2. The highest product prices determined from the sensitivity analysis resulted from an assumption of a zero inflation rate at an interest rate on debt of 11%. This is believed to be an upper bound on product prices. The determined values were:

Bowron coalfield:	SNG	- January 1983, $5.94/GJ;
	Syngas	- January 1983, $5.05/GJ
Tulameen coalfield:	SNG	- January 1983, $5.06/GJ
	Syngas	- January 1983, $4.22/GH

3. Considering the proximity of the Inland Natural Gas pipeline to the Tulameen coalfield, SNG is the preferred product.

   Syngas would have to be transported to a user in a dedicated line. A potential industrial user of this product for synthesis of chemical products does not exist nearby.

4. Based on the identified reserve for the Tulameen coalfield, nominal plant capacities of up to 6.5 X 10^6 m^3/d SNG or 16.4 X 10^6 m^3/d syngas could be supported. SNG and syngas prices would decrease from the predicted values with increasing plant sizes due to economies of scale.

5. To build a prototype underground coal gasification plant at the Tulameen coalfield, a 6- to 10-year program of process modeling, laboratory experimentation, and field trials is required. A major portion of the work in areas of process modeling and laboratory experimentation should precede any field trials.

   The budget cost for site characterization and a series of four field trials of increasing scale is $10,500,000. This cost does not include any major complimentary studies and laboratory experimentation that may be needed while the field trials are being undertaken. The budget cost of a detailed geological and hydrogeological study is $500,000.

6. The following list identifies some of the initial work that would have to be undertaken if underground coal gasification is to be applied in the Tulameen coalfield; a more thorough discussion of the development work that would be needed is given in Chapter X.

   a) A study should be undertaken to refine the estimate of product gas yield and quality using computer process models available at, for example, the Laramie Energy Technology Centre. To conduct this work, the composition of coal samples from the coalfield would have to be determined.

   b) An inspection of the coalfield should be made to map the topography and surficial geology of the area and obtain data which is needed for siting and designing the gasification and plant areas.

   c) A study of the environmental impact of the process should be conducted using data from pilot tests conducted elsewhere. These data would identify the type and yield of contaminants, effects of subsidence, extent of groundwater contamination, and effect of the process on regional groundwater flow, among other factors.

   d) To ascertain whether there would be unacceptable contamination of groundwater flows and a hazard to downstream users of this water, and to supply data for possible field testing, a hydrogeological study should be undertaken. This study would require the drilling of several wells, coring of the formation to define rock types, and computer modeling of groundwater flow. Data obtained in c) above would be used in this study as input data and to confirm predictions of contaminant migration.

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APPENDIX A

GEOLOGICAL CHARACTERISTICS OF THE BOWRON AND TULAMEEN COALFIELDS WITH RESPECT TO UNDERGROUND GASIFICATION

(UNDER SEPARATE COVER)

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APPENDIX B ECONOMIC ANALYSIS

A. ECONOMIC ASSUMPTIONS

Table B-1 lists the economic assumptions used in the financial analysis.

B. CASH FLOW TABLES FOR BASE CASES

Tables B-2 to B-5 present cash flow tabulations for the base cases of SNG and syngas production at each coalfield.

Table B-1

LIST OF ECONOMIC PARAMETERS FOR BASE CASE ANALYSIS

1.	Period of Analysis	1983 - 2005 3-year construction period 20-year operating life
2.	Schedule of Capital Spending During Construction	1983 10% 1984 40% 1985 50%
3.	Plant Capacity Factor	1986 50% 1987 - 2006 90%
4.	Long-Term Debt-Interest Rate	11%
5.	Source of Financing	100% debt
6.	Depreciation	Land and working capital not depreciable. Straight-line depreciation over 20-year operating life.
7.	Inflation Rate	All costs and revenue inflate at 7% per year.
8.	Income Taxes	None
9.	Salvage Values of Plant and Land	Nil
10.	Timing of Costs	Investments made at start of year. Operating expenses paid at end of year.
11.	Working Capital	Working capital recovered intact at end of operating life.
12.	Interest During Construction	Interest on capital during construction is added to borrowed capital. Interest calculated on 100% of debt at start of year.
13.	Debt Recovery	Debt principle repaid with revenue after expenses and interest starting in 1986.

14. Coal is consumed without any specific feedstock cost.

15. Capital and operating costs determined in mid-1982 dollars. Costs subsequently inflated 3.5% to update to January 1983 dollars.

16. Product prices in January 1983 were determined to make a specified return to debt and cover all annual operating expenses over the operating life such that there is zero outstanding capital at the end of plant life.

TABLE B-2

PAYOUT TABULATION: BOWRON COALFIELD - SNG BASE CASE

Product Price = January 1983 $ 4.19/GJ

100% Debt at 11%

	1 CPSTRT	2 EFFNCY	3 INCOME	4 PLTEXP	5 STLTAX	6 TXCRDT	7 FEDTAX	8 CASHFL	9 TOTRTN	10 AMORTZ	11 CAPEND
1	44.2700	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-4.8697	-4.8697	48.1397
2	183.9785	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-20.1176	-20.1176	201.1041
3	384.1157	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-42.0327	-42.0327	434.3444
4	444.1326	0.5000	55.1282	50.3369	3.4411	0.0000	0.0000	1.3502	49.1425	-47.9141	513.3982
5	494.9669	0.9000	106.1769	67.2508	3.4411	0.0000	0.0000	35.4858	84.4463	-18.9611	532.3592
6	511.9282	0.9000	113.6093	71.5972	3.4411	0.0000	0.0000	38.5710	88.5327	-16.9346	548.2938
7	511.8893	0.9000	121.5619	76.2476	3.4411	0.0000	0.0000	41.8732	92.8078	-14.7928	563.0866
8	511.5239	0.9000	130.0713	81.2235	3.4411	0.0000	0.0000	45.4067	97.2176	-12.5309	575.6176
9	510.7548	0.9000	139.1763	86.5480	3.4411	0.0000	0.0000	49.1872	101.8800	-10.1527	585.7703
10	509.6476	0.9000	148.9186	92.2450	3.4411	0.0000	0.0000	53.2325	106.7872	-8.0432	593.8135
11	508.4023	0.9000	159.3429	98.3408	3.4411	0.0000	0.0000	57.5610	111.9042	-5.6756	599.4891
12	507.3455	0.9000	170.4969	104.8634	3.4411	0.0000	0.0000	62.1924	117.2680	-3.0756	602.5647
13	506.4711	0.9000	182.4317	111.8429	3.4411	0.0000	0.0000	67.1481	122.9063	-0.5418	603.1065
14	505.8291	0.9000	195.2019	119.3102	3.4411	0.0000	0.0000	72.4506	128.7367	2.0319	601.0746
15	505.4854	0.9000	208.8661	127.3005	3.4411	0.0000	0.0000	78.1245	134.6651	4.4594	596.6152
16	505.4060	0.9000	223.4867	135.8503	3.4411	0.0000	0.0000	84.1953	140.7846	6.8107	589.8045
17	505.5353	0.9000	239.1308	144.9985	3.4411	0.0000	0.0000	90.6912	146.8734	8.8178	581.0867
18	505.7775	0.9000	255.8699	154.7871	3.4411	0.0000	0.0000	97.6417	152.5935	10.0482	571.0385
19	506.1291	0.9000	273.7808	165.2609	3.4411	0.0000	0.0000	105.0788	157.1882	10.2563	560.7822
20	506.5024	0.9000	292.9455	176.4679	3.4411	0.0000	0.0000	113.0365	159.4802	8.9263	551.8559
21	506.8974	0.9000	313.4517	188.4593	3.4411	0.0000	0.0000	121.5513	160.2690	6.2823	545.5736
22	507.3001	0.9000	335.3913	201.2902	3.4411	0.0000	0.0000	130.6620	157.3280	2.3340	543.2396
23	508.4661	0.9000	358.8708	172.5806	3.4411	0.0000	0.0000	182.0791	20.4012	162.4779	22.9882

THE LAST ENTRY IN THE FINAL YEAR SHOULD BE EQUAL TO THE WORKING CAPITAL INVESTMENT PLUS SALVAGE VALUE PLUS LAND SALE VALUE

WORKING CAPITAL RECOVERED INTACT AT END OF PROJECT LIFE = 22.98420

LAND SALE VALUE RECOVERED AT END OF PROJECT LIFE = 0.00000

SALVAGE VALUE RECOVERED INTACT AT END OF PROJECT LIFE = 0.00000

TOTAL 22.98420

KEY TO CALCULATIONS IS AS FOLLOWS:

COLUMN 1 = CAPITAL INVESTMENT OUTSTANDING AT START OF YEAR INCLUDING WORKING CAPITAL

COLUMN 2 = ONSTREAM EFFICIENCY (PART OPERATING FACTOR)

COLUMN 3 = GROSS INCOME FROM SALES

COLUMN 4 = OPERATING EXPENSES EXCLUDING TAXES

COLUMN 5 = STATE AND LOCAL TAXES

COLUMN 6 = FEDERAL INVESTMENT TAX CREDIT

COLUMN 7 = NET FEDERAL INCOME TAX PAID

COLUMN 8 = CASH FLOW AFTER TAXES

COLUMN 9 = INTEREST ON DEBT AND RETURN ON EQUITY BASED ON COLUMN 1

COLUMN 10 = REDUCTION OF OUTSTANDING CAPITAL

COLUMN 11 = OUTSTANDING CAPITAL INVESTMENT AT END OF YEAR INCL WORKING CAPITAL COL 1-10 PLUS NEW INVESTMENT = NEXT ENTRY OF COLUMN 1

TABLE B-2 (CONTINUED)

	1 CPSTRT	2 DEPREC	3 INTRST	4 COVRGE	5 TXCRDT	6 TAXABL	7 FEDTAX	8 STTAXBL	9 EQYRTN	10 PROPTY	11 FEDTXN
1	44.2700	0.0000	4.8697	1.4609	0.0000	-4.8697	0.0000	-4.8697	0.0000	0.0000	0.0000
2	182.9785	0.0000	20.1276	5.0382	0.0000	-20.1276	0.0000	-20.1276	0.0000	0.0000	0.0000
3	383.1157	0.0000	42.0327	12.6098	0.0000	-42.0327	0.0000	-42.0327	0.0000	3.4411	0.0000
4	447.1326	17.2059	49.1845	14.7553	0.0000	-65.0402	0.0000	-61.5991	0.0000	3.4411	0.0000
5	494.9669	17.2059	54.4463	16.3338	0.0000	-36.1672	0.0000	-32.7261	0.0000	3.4411	0.0000
6	513.9282	17.2059	56.5321	16.9596	0.0000	-35.1670	0.0000	-31.7259	0.0000	3.4411	0.0000
7	531.8893	17.2059	58.5078	17.5523	0.0000	-33.8405	0.0000	-30.3994	0.0000	3.4411	0.0000
8	548.5239	17.2059	60.3376	18.1012	0.0000	-32.1368	0.0000	-28.6957	0.0000	3.4411	0.0000
9	563.4848	17.2059	61.9800	18.5940	0.0000	-29.9987	0.0000	-26.5576	0.0000	3.4411	0.0000
10	576.2476	17.2059	63.3872	19.0161	0.0000	-27.3606	0.0000	-23.9195	0.0000	3.4411	0.0000
11	586.4023	17.2059	64.5042	19.3512	0.0000	-24.1491	0.0000	-20.7080	0.0000	3.4411	0.0000
12	593.3455	17.2059	65.2680	19.5804	0.0000	-20.2815	0.0000	-16.8404	0.0000	3.4411	0.0000
13	596.4211	17.2059	65.6063	19.6818	0.0000	-15.6641	0.0000	-12.2230	0.0000	3.4411	0.0000
14	594.8793	17.2059	65.4367	19.6310	0.0000	-10.1920	0.0000	-6.7509	0.0000	3.4411	0.0000
15	587.8654	17.2059	64.6651	19.3995	0.0000	-3.7465	0.0000	-0.3054	0.0000	3.4411	0.0000
16	574.4060	17.2059	63.1846	18.9553	0.0000	3.8048	0.0000	7.2459	0.0000	3.4411	0.0000
17	553.1953	17.2059	60.8734	18.2620	0.0000	12.6119	0.0000	16.0530	0.0000	3.4411	0.0000
18	523.5775	17.2059	57.5935	17.2780	0.0000	21.8423	0.0000	26.2834	0.0000	3.4411	0.0000
19	483.5293	17.2059	53.1882	15.9564	0.0000	31.6847	0.0000	38.1258	0.0000	3.4411	0.0000
20	431.6387	17.2059	47.4802	14.2440	0.0000	44.3504	0.0000	51.7915	0.0000	3.4411	0.0000
21	366.0824	17.2059	40.2690	12.0807	0.0000	64.0764	0.0000	67.5175	0.0000	3.4411	0.0000
22	284.8001	17.2059	31.3280	9.3984	0.0000	85.1281	0.0000	85.5692	0.0000	3.4411	0.0000
23	185.4661	17.2059	20.4012	6.1203	0.0000	145.2720	0.0000	148.7131	0.0000	3.4411	0.0000

KEY TO CALCULATIONS IS AS FOLLOWS:
COLUMN 1 = TOTAL CAPITAL AT START OF YEAR
COLUMN 2 = DEPRECIATION ALLOWANCE FOR TAXES
COLUMN 3 = INTEREST ON DEBT
COLUMN 4 = INTEREST COVERAGE (30%)
COLUMN 5 = INVESTMENT TAX CREDIT TAKEN THIS YEAR
COLUMN 6 = FEDERAL TAXABLE INCOME
COLUMN 7 = FEDERAL INCOME TAX PAID
COLUMN 8 = STATE TAXABLE INCOME
COLUMN 9 = AFTER-TAX RETURN ON EQUITY
COLUMN 10 = LOCAL PROPERTY TAX PAID
COLUMN 11 = CALCULATED FEDERAL INCOME TAX PRIOR TO NONNEGATIVITY CONSTRAINT

TABLE B-3

PAYOUT TABULATION: BOWRON COALFIELD - SYNGAS BASE CASE

Product Price = January 1983 $ 3.58/GJ 100% Debt at 11%

	1 CPSTRT	2 EFFNCY	3 INCOME	4 PLTEXP	5 STLTAX	6 TXCRDT	7 FEDTAX	8 CASHFL	9 TOTRTN	10 AMORTZ	11 CAPEND
1	40.5640	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	4.4620	-4.4620	45.0260
2	162.9988	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	17.9298	-17.9298	180.9286
3	338.7187	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	37.2590	-37.2590	375.9777
4	396.2374	0.5000	49.8632	45.7638	3.0332	0.0000	0.0000	1.0662	43.5861	-42.5199	434.7573
5	438.7573	0.9000	96.0365	61.5837	3.0332	0.0000	0.0000	31.4196	48.2633	-16.8437	455.6010
6	455.6010	0.9000	102.7590	65.5761	3.0332	0.0000	0.0000	34.1497	50.1161	-15.9664	471.5674
7	471.5674	0.9000	109.9522	69.8479	3.0332	0.0000	0.0000	37.0711	51.8724	-14.8013	486.3687
8	486.3687	0.9000	117.6488	74.4188	3.0332	0.0000	0.0000	40.1968	53.5005	-13.3037	499.6724
9	499.6724	0.9000	125.8843	79.3096	3.0332	0.0000	0.0000	43.5415	54.9639	-11.4224	511.0948
10	511.0948	0.9000	134.6962	84.5428	3.0332	0.0000	0.0000	47.1202	56.2204	-9.1002	520.1950
11	520.1950	0.9000	144.1249	90.1423	3.0332	0.0000	0.0000	50.9494	57.2214	-6.2720	526.4670
12	526.4670	0.9000	154.2136	96.1338	3.0332	0.0000	0.0000	55.0466	57.9113	-2.8647	529.3317
13	529.3317	0.9000	165.0086	102.5446	3.0332	0.0000	0.0000	59.4308	58.2264	1.2044	528.1273
14	528.1273	0.9000	176.5592	109.4043	3.0332	0.0000	0.0000	64.1217	58.0940	6.0277	522.0996
15	522.0996	0.9000	188.9183	116.7441	3.0332	0.0000	0.0000	69.1410	57.4309	11.7101	510.3895
16	510.3895	0.9000	202.1426	124.5977	3.0332	0.0000	0.0000	74.5117	56.1428	18.3689	492.0206
17	492.0206	0.9000	216.2926	133.0011	3.0332	0.0000	0.0000	80.2583	54.1222	26.1361	465.8845
18	465.8845	0.9000	231.4331	141.9927	3.0332	0.0000	0.0000	86.4072	51.2472	35.1600	430.7245
19	430.7245	0.9000	247.6334	151.6137	3.0332	0.0000	0.0000	92.9865	47.3796	45.6069	385.1176
20	385.1176	0.9000	264.9678	161.9081	3.0332	0.0000	0.0000	100.0265	42.3629	57.6636	327.4540
21	327.4540	0.9000	283.5155	172.9233	3.0332	0.0000	0.0000	107.5590	36.0199	71.5391	255.9149
22	255.9149	0.9000	303.3616	184.7094	3.0332	0.0000	0.0000	115.6190	28.1506	87.4684	168.4465
23	168.4465	0.9000	324.5969	154.8521	3.0332	0.0000	0.0000	166.7116	18.5291	148.1825	20.2640

THE LAST ENTRY IN THE FINAL YEAR SHOULD BE EQUAL TO THE WORKING CAPITAL INVESTMENT PLUS SALVAGE VALUE PLUS LAND SALE VALUE

WORKING CAPITAL RECOVERED INTACT AT END OF PROJECT LIFE = 20.25970

LAND SALE VALUE RECOVERED AT END OF PROJECT LIFE = 0.00000
SALVAGE VALUE RECOVERED INTACT AT END OF PROJECT LIFE = 0.00000
TOTAL 20.25970

KEY TO CALCULATIONS IS AS FOLLOWS:
COLUMN 1 = CAPITAL INVESTMENT OUTSTANDING AT START OF YEAR INCLUDING WORKING CAPITAL
COLUMN 2 = ONSTREAM EFFICIENCY (PANT OPERATING FACTOR)
COLUMN 3 = GROSS INCOME FROM SALES
COLUMN 4 = OPERATING EXPENSES EXCLUDING TAXES
COLUMN 5 = STATE AND LOCAL TAXES
COLUMN 6 = FEDERAL INVESTMENT TAX CREDIT
COLUMN 7 = NET FEDERAL INCOME TAX PAID
COLUMN 8 = CASH FLOW AFTER TAXES
COLUMN 9 = INTEREST ON DEBT AND RETURN ON EQUITY BASED ON COLUMN 1
COLUMN 10 = REDUCTION OF OUTSTANDING CAPITAL
COLUMN 11 = OUTSTANDING CAPITAL INVESTMENT AT END OF YEAR INCL WORKING CAPITAL COL 1-10
COLUMN 11 = PLUS NEW INVESTMENT = NEXT ENTRY OF COLUMN 1

TABLE B-3 (CONTINUED)

	1 CPSTRT	2 DEPREC	3 INTRST	4 COVRGE	5 TXCRDT	6 TAXABL	7 FEDTAX	8 STXABL	9 EQYRTN	10 PROPTY	11 FEDTAN
1	40.5640	0.0000	4.4620	1.3386	0.0000	-4.4620	0.0000	-4.4620	0.0000	0.0000	0.0000
2	162.9988	0.0000	17.9298	5.3789	0.0000	-17.9298	0.0000	-17.9298	0.0000	0.0000	0.0000
3	338.7187	0.0000	37.2590	11.1777	0.0000	-37.2590	0.0000	-37.2590	0.0000	0.0000	0.0000
4	496.2374	15.1663	43.5861	13.0758	0.0000	-57.6862	0.0000	-54.6530	0.0000	3.0332	0.0000
5	438.7573	15.1663	48.2633	14.4789	0.0000	-32.0100	0.0000	-28.9768	0.0000	3.0332	0.0000
6	455.6010	15.1663	50.1161	15.0348	0.0000	-31.1327	0.0000	-28.0995	0.0000	3.0332	0.0000
7	471.9674	15.1663	51.8724	15.5617	0.0000	-29.9676	0.0000	-26.9344	0.0000	3.0332	0.0000
8	488.3887	15.1663	53.5005	16.0501	0.0000	-28.4700	0.0000	-25.4368	0.0000	3.0332	0.0000
9	499.6724	15.1663	54.9639	16.4891	0.0000	-26.5887	0.0000	-23.5555	0.0000	3.0332	0.0000
10	511.0948	15.1663	56.2204	16.8661	0.0000	-24.2665	0.0000	-21.2333	0.0000	3.0332	0.0000
11	520.1950	15.1663	57.2214	17.1664	0.0000	-21.4383	0.0000	-18.4051	0.0000	3.0332	0.0000
12	526.4670	15.1663	57.9113	17.3733	0.0000	-18.0310	0.0000	-14.9978	0.0000	3.0332	0.0000
13	529.3317	15.1663	58.2264	17.4679	0.0000	-13.9619	0.0000	-10.9287	0.0000	3.0332	0.0000
14	528.1273	15.1663	58.0940	17.4282	0.0000	-9.1386	0.0000	-6.1054	0.0000	3.0332	0.0000
15	522.0996	15.1663	57.4309	17.2292	0.0000	-3.4562	0.0000	-0.4230	0.0000	3.0332	0.0000
16	510.3495	15.1663	56.1428	16.8428	0.0000	3.2026	0.0000	6.2358	0.0000	3.0332	0.0000
17	492.0206	15.1663	54.1222	16.2366	0.0000	10.9698	0.0000	14.0030	0.0000	3.0332	0.0000
18	465.6445	15.1663	51.2472	15.3741	0.0000	19.9937	0.0000	23.0269	0.0000	3.0332	0.0000
19	430.7245	15.1663	47.3796	14.2138	0.0000	30.4406	0.0000	33.4738	0.0000	3.0332	0.0000
20	385.1176	15.1663	42.3629	12.7088	0.0000	42.4973	0.0000	45.5305	0.0000	3.0332	0.0000
21	327.4540	15.1663	36.0199	10.8059	0.0000	56.3728	0.0000	59.4060	0.0000	3.0332	0.0000
22	255.9149	15.1663	28.1506	8.4451	0.0000	72.3021	0.0000	75.3353	0.0000	3.0332	0.0000
23	168.4465	15.1663	18.5291	5.5587	0.0000	133.0162	0.0000	136.0494	0.0000	3.0332	0.0000

KEY TO CALCULATIONS IS AS FOLLOWS:
COLUMN 1 = TOTAL CAPITAL AT START OF YEAR
COLUMN 2 = DEPRECIATION ALLOWANCE FOR TAXES
COLUMN 3 = INTEREST ON DEBT
COLUMN 4 = INTEREST COVERAGE (30%)
COLUMN 5 = INVESTMENT TAX CREDIT TAKEN THIS YEAR
COLUMN 6 = FEDERAL TAXABLE INCOME
COLUMN 7 = FEDERAL INCOME TAX PAID
COLUMN 8 = STATE TAXABLE INCOME
COLUMN 9 = AFTER-TAX RETURN ON EQUITY
COLUMN 10 = LOCAL PROPERTY TAX PAID
COLUMN 11 = CALCULATED FEDERAL INCOME TAX PRIOR TO NONNEGATIVITY CONSTRAINT

TABLE B-4

PAYOUT TABULATION: TULAMEEN COALFIELD - SNG BASE CASE

Product Price = January 1983 $ 3.37/GJ 100% Debt at 11%

	1 CPSTRT	2 EFFNCY	3 INCOME	4 PLTEXP	5 STLTAX	6 TXCRDT	7 FEDTAX	8 CASHFL	9 TOTRTN	10 AMORTZ	11 CAPEND
1	38.6980	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-4.2567	-4.2567	42.9547
2	174.3432	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	19.1777	-19.1777	193.5709
3	369.2550	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	40.6180	-40.6180	409.8730
4	432.4370	0.5000	44.4671	40.2162	3.3782	0.0000	0.0000	0.8727	47.5680	-46.6953	479.1274
5	479.1323	0.9000	85.6437	47.6963	3.3782	0.0000	0.0000	34.5692	52.7045	-18.1353	497.2626
6	497.2676	0.9000	91.6388	50.6804	3.3782	0.0000	0.0000	37.5802	54.6994	-17.1192	514.3818
7	514.3868	0.9000	98.0535	53.8733	3.3782	0.0000	0.0000	40.8020	56.5825	-15.7805	530.1623
8	530.1673	0.9000	104.9173	57.2858	3.3782	0.0000	0.0000	44.2493	58.3184	-14.0691	544.2314
9	544.2364	0.9000	112.2615	60.9452	3.3782	0.0000	0.0000	47.9381	59.8860	-11.9479	556.1793
10	556.1643	0.9000	120.1198	64.8568	3.3782	0.0000	0.0000	51.8848	61.1780	-9.2932	565.4725
11	565.4575	0.9000	128.5282	69.0420	3.3782	0.0000	0.0000	56.1080	62.2003	-6.0923	571.5648
12	571.5498	0.9000	137.5252	73.5203	3.3782	0.0000	0.0000	60.6267	62.8704	-2.2437	573.8085
13	573.7935	0.9000	147.1519	78.3120	3.3782	0.0000	0.0000	65.4617	63.1172	2.3445	571.4640
14	571.4490	0.9000	157.4526	83.4391	3.3782	0.0000	0.0000	70.6353	62.8593	7.7760	563.6730
15	563.6730	0.9000	168.4743	88.9252	3.3782	0.0000	0.0000	76.1709	62.0040	14.1669	549.5061
16	549.5061	0.9000	180.2675	94.7953	3.3782	0.0000	0.0000	82.0940	60.4456	21.6484	527.8577
17	527.8577	0.9000	192.8862	101.0762	3.3782	0.0000	0.0000	88.4318	58.0643	30.3675	497.4902
18	497.4902	0.9000	206.3882	107.7968	3.3782	0.0000	0.0000	95.2132	54.7239	40.4893	457.0009
19	457.0009	0.9000	220.8354	114.9879	3.3782	0.0000	0.0000	102.4693	50.2700	52.1993	404.8016
20	404.8016	0.9000	236.2939	122.6823	3.3782	0.0000	0.0000	110.2334	44.5281	65.7053	339.0963
21	339.0963	0.9000	252.8344	130.9154	3.3782	0.0000	0.0000	118.5408	37.3005	81.2403	257.8560
22	257.8560	0.9000	270.5329	139.7247	3.3782	0.0000	0.0000	127.4300	28.3641	99.0659	158.7901
23	158.7901	0.9000	289.4702	132.4049	3.3782	0.0000	0.0000	153.6871	17.4669	136.2202	22.5699

THE LAST ENTRY IN THE FINAL YEAR SHOULD BE EQUAL TO THE WORKING CAPITAL INVESTMENT PLUS SALVAGE VALUE PLUS LAND SALE VALUE

WORKING CAPITAL RECOVERED INTACT AT END OF PROJECT LIFE = 22.56490

LAND SALE VALUE RECOVERED AT END OF PROJECT LIFE = 0.00000
SALVAGE VALUE RECOVERED INTACT AT END OF PROJECT LIFE = 0.00000
TOTAL 22.56400

KEY TO CALCULATIONS IS AS FOLLOWS:
COLUMN 1 = CAPITAL INVESTMENT OUTSTANDING AT START OF YEAR INCLUDING WORKING CAPITAL
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COLUMN 3 = GROSS INCOME FROM SALES
COLUMN 4 = OPERATING EXPENSES EXCLUDING TAXES
COLUMN 5 = STATE AND LOCAL TAXES
COLUMN 6 = FEDERAL INVESTMENT TAX CREDIT
COLUMN 7 = NET FEDERAL INCOME TAX PAID
COLUMN 8 = CASH FLOW AFTER TAXES
COLUMN 9 = INTEREST ON DEBT AND RETURN ON EQUITY BASED ON COLUMN 1
COLUMN 10 = REDUCTION OF OUTSTANDING CAPITAL
COLUMN 11 = OUTSTANDING CAPITAL INVESTMENT AT END OF YEAR INCL WORKING CAPITAL COL 1-10
COLUMN 11 = PLUS NEW INVESTMENT = NEXT ENTRY OF COLUMN 1

TABLE B-4 (CONTINUED)

	1 CPSTRT	2 DEPREC	3 INTRST	4 COVRGE	5 TXCRDT	6 TAXARL	7 FEDTAX	8 STTXBL	9 EQTRTN	10 PROPTX	11 FEDTAX
1	31.6980	0.0000	4.2567	1.2770	0.0000	-4.2567	0.0000	-4.2567	0.0000	0.0000	0.0000
2	114.3432	0.0000	19.1777	5.7533	0.0000	-19.1777	0.0000	-19.1777	0.0000	0.0000	0.0000
3	369.2550	0.0000	40.6180	12.1854	0.0000	-40.6180	0.0000	-40.6180	0.0000	3.3782	0.0000
4	432.4170	16.8910	47.5600	14.2704	0.0000	-63.5863	0.0000	-60.2081	0.0000	3.3782	0.0000
5	478.1323	16.8910	52.7045	15.8113	0.0000	-35.0263	0.0000	-31.6481	0.0000	3.3782	0.0000
6	497.2676	16.8910	54.6994	16.4098	0.0000	-34.0102	0.0000	-30.6320	0.0000	3.3782	0.0000
7	514.3868	16.8910	56.5825	16.9747	0.0000	-32.6915	0.0000	-29.3133	0.0000	3.3782	0.0000
8	530.1671	16.8910	58.3114	17.4955	0.0000	-30.9601	0.0000	-27.5819	0.0000	3.3782	0.0000
9	544.2364	16.8910	59.8660	17.9598	0.0000	-28.8189	0.0000	-25.4407	0.0000	3.3782	0.0000
10	556.1643	16.8910	61.1780	18.3534	0.0000	-26.1842	0.0000	-22.8060	0.0000	3.3782	0.0000
11	565.4575	16.8910	62.2003	18.6600	0.0000	-22.9833	0.0000	-19.6051	0.0000	3.3782	0.0000
12	571.5498	16.8910	62.8704	18.8611	0.0000	-19.1347	0.0000	-15.7565	0.0000	3.3782	0.0000
13	573.7935	16.8910	63.1172	18.9351	0.0000	-14.5485	0.0000	-11.1703	0.0000	3.3782	0.0000
14	571.4490	16.8910	62.8593	18.8577	0.0000	-9.1150	0.0000	-5.7368	0.0000	3.3782	0.0000
15	563.6730	16.8910	62.0040	18.6012	0.0000	-2.7241	0.0000	0.6541	0.0000	3.3782	0.0000
16	549.5061	16.8910	60.4456	18.1336	0.0000	4.7574	0.0000	8.1356	0.0000	3.3782	0.0000
17	527.8577	16.8910	58.0643	17.4192	0.0000	13.4765	0.0000	16.8547	0.0000	3.3782	0.0000
18	497.4402	16.8910	54.7239	16.4171	0.0000	23.5983	0.0000	26.9765	0.0000	3.3782	0.0000
19	457.0009	16.8910	50.2700	15.0810	0.0000	35.3083	0.0000	38.6865	0.0000	3.3782	0.0000
20	404.8016	16.8910	44.5281	13.3584	0.0000	48.8143	0.0000	52.1925	0.0000	3.3782	0.0000
21	339.0963	16.8910	37.3005	11.1901	0.0000	64.3493	0.0000	67.7275	0.0000	3.3782	0.0000
22	257.8560	16.8910	28.3641	8.5092	0.0000	82.1749	0.0000	85.5531	0.0000	3.3782	0.0000
23	159.7901	16.8910	17.4669	5.2400	0.0000	119.3292	0.0000	122.7074	0.0000	3.3782	0.0000

KEY TO CALCULATIONS IS AS FOLLOWS:
COLUMN 1 = TOTAL CAPITAL AT START OF YEAR
COLUMN 2 = DEPRECIATION ALLOWANCE FOR TAXES
COLUMN 3 = INTEREST ON DEBT
COLUMN 4 = INTEREST COVERAGE (30%)
COLUMN 5 = INVESTMENT TAX CREDIT TAKEN THIS YEAR
COLUMN 6 = FEDERAL TAXABLE INCOME
COLUMN 7 = FEDERAL INCOME TAX PAID
COLUMN 8 = STATE TAXABLE INCOME
COLUMN 9 = AFTER-TAX RETURN ON EQUITY
COLUMN 10 = LOCAL PROPERTY TAX PAID
COLUMN 11 = CALCULATED FEDERAL INCOME TAX PRIOR TO NONNEGATIVITY CONSTRAINT

TABLE B-5

PAYOUT TABULATION: TULAMEEN COALFIELD - SYNGAS BASE CASE

Product Price: January 1983 $ 2.81/GJ

100% Debt at 11%

	1 CPSTRT	2 EFFNCI	3 INCOME	4 PLTEXP	5 STLTAX	6 TXCRDT	7 FEDTAX	8 CASHFL	9 TOTRTN	10 AMORTZ	11 CAPEND
1	34.9920	0.6000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-3.8491	-3.8491	38.8411
2	154.3647	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-16.9801	-16.9801	171.3448
3	325.8582	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	-35.8444	-35.8444	361.7026
4	381.5421	0.5000	39.2021	35.6431	2.9702	0.0000	0.0000	0.5888	41.9696	-41.3808	423.0834
5	422.9229	0.9000	75.5032	42.0291	2.9702	0.0000	0.0000	30.5039	44.5215	-14.0176	438.9405
6	438.9405	0.9000	80.7884	44.6592	2.9702	0.0000	0.0000	33.1590	48.2834	-15.1244	454.0649
7	454.0649	0.9000	86.4436	47.4536	2.9702	0.0000	0.0000	35.9998	49.9471	-13.9473	468.0122
8	468.0122	0.9000	92.4947	50.4847	2.9702	0.0000	0.0000	39.0398	51.4811	-12.4415	480.4537
9	480.4537	0.9000	98.9693	53.7068	2.9702	0.0000	0.0000	42.2923	54.8408	-12.5576	493.0113
10	493.0113	0.9000	105.8972	57.1544	2.9702	0.0000	0.0000	45.7726	54.0112	-8.2386	501.2499
11	501.2499	0.9000	113.3100	60.8435	2.9702	0.0000	0.0000	49.4963	54.9174	-5.4211	506.6710
12	506.6710	0.9000	121.2417	64.7906	2.9702	0.0000	0.0000	53.4809	55.5138	-2.0329	508.7039
13	508.7039	0.9000	129.7286	69.0140	2.9702	0.0000	0.0000	57.7444	55.7374	-2.0070	510.7109
14	510.7109	0.9000	138.8096	73.5332	2.9702	0.0000	0.0000	62.3062	55.5166	-2.7896	513.4993
15	513.4993	0.9000	148.5263	78.3686	2.9702	0.0000	0.0000	67.1875	54.7698	-12.4177	525.9170
16	525.9170	0.9000	158.9231	83.5425	2.9702	0.0000	0.0000	72.4104	53.4038	-19.0066	544.9236
17	544.9236	0.9000	170.0478	89.0786	2.9702	0.0000	0.0000	77.9990	51.3131	-26.6859	571.6095
18	571.6095	0.9000	181.9511	95.0022	2.9702	0.0000	0.0000	83.9767	48.3776	-35.6011	607.2106
19	607.2106	0.9000	194.6877	101.3406	2.9702	0.0000	0.0000	90.3769	44.4615	-45.9154	653.1260
20	653.1260	0.9000	208.3158	108.1225	2.9702	0.0000	0.0000	97.2231	39.4108	-58.7123	711.8383
21	711.8383	0.9000	222.8979	115.3792	2.9702	0.0000	0.0000	104.5485	33.0515	-71.4970	783.3353
22	783.3353	0.9000	238.5008	123.1439	2.9702	0.0000	0.0000	112.3867	25.1068	-87.1999	870.5352
23	870.5352	0.9000	255.1959	131.4524	2.9702	0.0000	0.0000	120.8139	15.5948	-105.2191	975.7543
24	975.7543	0.9000	273.0597	140.3434	2.9702	0.0000	0.0000	129.8176	4.3911	-125.4265	1101.1808
25	1101.1808	0.9000	292.1839	149.8585	2.9702	0.0000	0.0000	139.4911	-8.8336	-148.3247	1249.5055
26	1249.5055	0.9000	312.6668	160.0424	2.9702	0.0000	0.0000	150.0344	-23.1980	-173.2324	1422.7379
27	1422.7379	0.9000	334.6133	170.9433	2.9702	0.0000	0.0000	161.4539	-39.9827	-201.2366	1624.0245
28	1624.0245	0.9000	358.1362	182.6127	2.9702	0.0000	0.0000	173.8638	-59.3151	-233.1789	1857.2034
29	1857.2034	0.9000	383.3557	195.1060	2.9702	0.0000	0.0000	187.3990	-81.3772	-268.7762	2125.9796
30	2125.9796	0.9000	410.4005	208.4826	2.9702	0.0000	0.0000	201.9966	-106.3564	-308.3330	2434.3126
31	2434.3126	0.9000	439.4085	222.8064	2.9702	0.0000	0.0000	217.8026	-134.4744	-352.2770	2786.5896
32	2786.5896	0.9000	470.5276	238.1464	2.9702	0.0000	0.0000	234.8707	-166.0757	-401.9464	3188.5360
33	3188.5360	0.9000	504.0172	254.5771	2.9702	0.0000	0.0000	253.2644	-201.4127	-458.6771	3647.2131
34	3647.2131	0.9000	540.0488	272.1795	2.9702	0.0000	0.0000	273.0429	-241.8224	-523.8353	4171.0484
35	4171.0484	0.9000	578.8073	291.0413	2.9702	0.0000	0.0000	294.2660	-287.7824	-598.0484	4769.0968
36	4769.0968	0.9000	620.4917	311.2577	2.9702	0.0000	0.0000	317.1340	-339.8577	-683.2401	5452.3369
37	5452.3369	0.9000	665.3161	332.9318	2.9702	0.0000	0.0000	341.8481	-398.6679	-780.5160	6233.0529
38	6233.0529	0.9000	713.5116	356.1770	2.9702	0.0000	0.0000	368.6174	-465.0604	-892.1778	7125.2307
39	7125.2307	0.9000	765.3277	381.1181	2.9702	0.0000	0.0000	397.6596	-540.0681	-1019.7285	8145.0992
40	8145.0992	0.9000	821.0338	407.8936	2.9702	0.0000	0.0000	429.1999	-624.8938	-1165.4937	9310.5929
41	9310.5929	0.9000	880.9210	436.6571	2.9702	0.0000	0.0000	463.4733	-720.9838	-1332.1875	10642.7804
42	10642.7804	0.9000	945.3044	467.5781	2.9702	0.0000	0.0000	500.8351	-829.9132	-1523.2500	12166.0304
43	12166.0304	0.9000	1014.5256	500.8437	2.9702	0.0000	0.0000	541.6556	-953.5693	-1741.2249	13907.2553
44	13907.2553	0.9000	1089.0550	536.6442	2.9702	0.0000	0.0000	586.3248	-1093.1190	-1990.4439	15897.6992
45	15897.6992	0.9000	1169.3950	575.1923	2.9702	0.0000	0.0000	635.2571	-1249.4647	-2276.5837	18174.2829
46	18174.2829	0.9000	1256.0837	616.8176	2.9702	0.0000	0.0000	688.8999	-1424.9838	-2603.4485	20777.7314
47	20777.7314	0.9000	1349.6977	661.8688	2.9702	0.0000	0.0000	747.6359	-1621.8329	-2977.4688	23755.2002
48	23755.2002	0.9000	1450.8553	710.7195	2.9702	0.0000	0.0000	812.0850	-1842.5148	-3405.0298	27160.2300
49	27160.2300	0.9000	1560.3181	763.7705	2.9702	0.0000	0.0000	882.8076	-2089.7256	-3894.2334	31054.4634
50	31054.4634	0.9000	1678.8944	821.4511	2.9702	0.0000	0.0000	960.4033	-2367.4544	-4451.8577	35506.3211
51	35506.3211	0.9000	1807.5427	884.1220	2.9702	0.0000	0.0000	1045.5150	-2679.9377	-5089.4727	40595.7938
52	40595.7938	0.9000	1947.3744	952.2787	2.9702	0.0000	0.0000	1138.8259	-3032.6215	-5818.4941	46414.2879
53	46414.2879	0.9000	2099.6564	1026.4540	2.9702	0.0000	0.0000	1241.0646	-3431.2189	-6653.2825	53067.5704
54	53067.5704	0.9000	2265.7144	1107.2218	2.9702	0.0000	0.0000	1353.1126	-3881.8316	-7613.1142	60680.6846
55	60680.6846	0.9000	2447.0373	1195.9999	2.9702	0.0000	0.0000	1476.0000	-4391.0000	-8722.0000	69402.6846
56	69402.6846	0.9000	2645.2800	1293.5999	2.9702	0.0000	0.0000	1610.8000	-4965.0000	-9956.0000	79358.6846
57	79358.6846	0.9000	2862.4800	1400.3999	2.9702	0.0000	0.0000	1758.8000	-5611.0000	-11369.0000	90727.6846
58	90727.6846	0.9000	3100.8000	1517.9999	2.9702	0.0000	0.0000	1921.2000	-6338.0000	-12990.0000	103717.6846
59	103717.6846	0.9000	3362.4000	1647.5999	2.9702	0.0000	0.0000	2099.2000	-7157.0000	-14847.0000	118564.6846
60	118564.6846	0.9000	3649.2000	1789.5999	2.9702	0.0000	0.0000	2294.4000	-8080.0000	-16970.0000	135534.6846
61	135534.6846	0.9000	3963.6000	1945.5999	2.9702	0.0000	0.0000	2508.4000	-9122.0000	-19394.0000	154928.6846
62	154928.6846	0.9000	4307.6000	2117.1999	2.9702	0.0000	0.0000	2743.2000	-10299.0000	-22169.0000	177097.6846
63	177097.6846	0.9000	4683.6000	2305.1999	2.9702	0.0000	0.0000	3000.8000	-11630.0000	-25345.0000	202442.6846
64	202442.6846	0.9000	5094.8000	2511.5999	2.9702	0.0000	0.0000	3283.2000	-13136.0000	-28978.0000	231420.6846
65	231420.6846	0.9000	5544.4000	2737.9999	2.9702	0.0000	0.0000	3592.4000	-14844.0000	-33132.0000	264552.6846
66	264552.6846	0.9000	6035.6000	2985.9999	2.9702	0.0000	0.0000	3930.8000	-16781.0000	-37879.0000	302431.6846
67	302431.6846	0.9000	6572.8000	3257.9999	2.9702	0.0000	0.0000	4301.2000	-18980.0000	-43302.0000	345733.6846
68	345733.6846	0.9000	7160.4000	3556.3999	2.9702	0.0000	0.0000	4706.8000	-21477.0000	-49497.0000	395230.6846
69	395230.6846	0.9000	7803.6000	3883.9999	2.9702	0.0000	0.0000	5150.8000	-24317.0000	-56580.0000	451810.6846
70	451810.6846	0.9000	8508.0000	4243.9999	2.9702	0.0000	0.0000	5636.4000	-27551.0000	-64680.0000	516490.6846
71	516490.6846	0.9000	9279.6000	4639.1999	2.9702	0.0000	0.0000	6168.0000	-31240.0000	-73949.0000	590439.6846
72	590439.6846	0.9000	10125.6000	5073.9999	2.9702	0.0000	0.0000	6749.6000	-35463.0000	-84513.0000	674952.6846
73	674952.6846	0.9000	11053.2000	5553.5999	2.9702	0.0000	0.0000	7385.6000	-40303.0000	-96540.0000	771492.6846
74	771492.6846	0.9000	12070.8000	6083.9999	2.9702	0.0000	0.0000	8080.8000	-45870.0000	-110270.0000	881762.6846
75	881762.6846	0.9000	13187.2000	6671.9999	2.9702	0.0000	0.0000	8840.4000	-52294.0000	-125868.0000	1007630.6846
76	1007630.6846	0.9000	14412.4000	7325.1999	2.9702	0.0000	0.0000	9670.8000	-59732.0000	-143662.0000	1151292.6846
77	1151292.6846	0.9000	15757.2000	8051.9999	2.9702	0.0000	0.0000	10579.2000	-68369.0000	-164000.0000	1315292.6846
78	1315292.6846	0.9000	17233.6000	8861.9999	2.9702	0.0000	0.0000	11573.2000	-78427.0000	-187270.0000	1502562.6846
79	1502562.6846	0.9000	18854.4000	9765.9999	2.9702	0.0000	0.0000	12661.2000	-90161.0000	-213900.0000	1716462.6846
80	1716462.6846	0.9000	20633.6000	10775.9999	2.9702	0.0000	0.0000	13852.4000	-103861.0000	-244360.0000	1960822.6846
81	1960822.6846	0.9000	22586.4000	11905.9999	2.9702	0.0000	0.0000	15156.8000	-119861.0000	-279160.0000	2239982.6846
82	2239982.6846	0.9000	24729.6000	13171.1999	2.9702	0.0000	0.0000	16586.4000	-138561.0000	-318960.0000	2558942.6846
83	2558942.6846	0.9000	27081.6000	14587.1999	2.9702	0.0000	0.0000	18154.8000	-160461.0000	-364560.0000	2923502.6846
84	2923502.6846	0.9000	29662.8000	16171.1999	2.9702	0.0000	0.0000	19876.8000	-186161.0000	-416960.0000	3340462.6846
85	3340462.6846	0.9000	32495.2000	17941.9999	2.9702	0.0000	0.0000	21768.4000	-216361.0000	-477160.0000	3817622.6846
86	3817622.6846	0.9000	35603.2000	19919.9999	2.9702	0.0000	0.0000	23847.2000	-251861.0000	-547360.0000	4364982.6846
87	4364982.6846	0.9000	39013.2000	22127.9999	2.9702	0.0000	0.0000	26132.4000	-293661.0000	-629160.0000	4994142.6846
88	4994142.6846	0.9000	42753.6000	24591.1999	2.9702	0.0000	0.0000	28644.8000	-342761.0000	-724560.0000	5718702.6846
89	5718702.6846	0.9000	46855.2000	27335.9999	2.9702	0.0000	0.0000	31408.4000	-400161.0000	-835560.0000	6554262.6846
90	6554262.6846	0.9000	51353.6000	30391.9999	2.9702	0.0000	0.0000	34449.2000	-467061.0000	-963160.0000	7517422.6846
91	7517422.6846	0.9000	56287.2000	33791.9999	2.9702	0.0000	0.0000	37796.4000	-545361.0000	-1109360.0000	8626782.6846
92	8626782.6846	0.9000	61699.2000	37571.9999	2.9702	0.0000	0.0000	41483.2000	-636061.0000	-1277160.0000	9903942.6846
93	9903942.6846	0.9000	67636.8000	41771.9999	2.9702	0.0000	0.0000	45548.4000	-741161.0000	-1469560.0000	11373502.6846
94	11373502.6846	0.9000	74152.8000	46435.1999	2.9702	0.0000	0.0000	50036.8000	-862661.0000	-1689560.0000	13063062.6846
95	13063062.6846	0.9000	81306.0000	51607.1999	2.9702	0.0000	0.0000	54998.4000	-1003561.0000	-1940160.0000	15003222.6846
96	15003222.6846	0.9000	89161.2000	57335.9999	2.9702	0.0000	0.0000	60489.2000	-1167861.0000	-2225360.0000	17228582.6846
97	17228582.6846	0.9000	97790.4000	63679.1999	2.9702	0.0000	0.0000	66571.2000	-1359561.0000	-2549160.0000	19777742.6846
98	19777742.6846	0.9000	107272.8000	70695.9999	2.9702	0.0000	0.0000	73314.4000	-1582661.0000	-2915560.0000	22693302.6846
99	22693302.6846	0.9000	117696.0000	78447.9999	2.9702	0.0000	0.0000	80796.8000	-1841161.0000	-3328560.0000	26021862.6846
100	26021862.6846	0.9000	129156.0000	87007.1999	2.9702	0.0000	0.0000	89104.8000	-2139061.0000	-3792160.0000	29814022.6846
101	29814022.6846	0.9000	141758.4000	96447.9999	2.9702	0.0000	0.0000	98330.4000	-2480361.0000	-4310360.0000	34124382.6846
102	34124382.6846	0.9000	155618.4000	106855.1999	2.9702	0.0000	0.0000	108588.8000	-2869061.0000	-4887160.0000	39011542.6846
103	39011542.6846	0.9000	170864.4000	118323.1999	2.9702	0.0000	0.0000	119940.8000	-3308161.0000	-5527560.0000	44539102.6846
104	44539102.6846	0.9000	187636.8000	130955.9999	2.9702	0.0000	0.0000	132592.4000	-3800661.0000	-6234560.0000	50773662.6846
105	50773662.6846	0.9000	206090.4000	144871.9999	2.9702	0.0000	0.0000	146404.8000	-4349561.0000	-7012160.0000	57785822.6846
106	57785822.6846	0.9000	226394.4000	160199.9999	2.9702	0.0000	0.0000	161332.4000	-4957861.0000	-7864360.0000	65650182.6846
107	65650182.6846	0.9000	248732.4000	177083.9999	2.9702	0.0000	0.0000	177648.8000	-5628561.0000	-8794160.0000	74444342.6846
108	74444342.6846	0.9000	273304.8000	195683.9999	2.9702	0.0000	0.0000	195620.8000	-6364661.0000	-9804560.0000	84249202.6846
109	84249202.6846	0.9000	300330.0000	216175.1999	2.9702	0.0000	0.0000	215154.8000	-7169161.0000	-10898560.0000	95147762.6846
110	95147762.6846	0.9000	330050.4000	238751.9999	2.9702	0.0000	0.0000	236688.4000	-8045061.0000	-12079160.0000	107226922.6846
111	107226922.6846	0.9000	362730.0000	263627.9999	2.9702	0.0000	0.0000	260356.8000	-8995361.0000	-13349360.0000	120576282.6846
112	120576282.6846	0.9000	398660.4000	291035.9999	2.9702	0.0000	0.0000	286392.4000	-10023061.0000	-14712160.0000	135288442.6846
113	135288442.6846	0.9000	438156.0000	321231.9999	2.9702	0.0000	0.0000	315031.2000	-11131161.0000	-16170560.0000	151459002.6846
114	151459002.6846	0.9000	481561.2000	354495.1999	2.9702	0.0000	0.0000	346534.8000	-12322661.0000	-17727560.0000	169186562.6846
115	169186562.6846	0.9000	529249.2000	391135.1999	2.9702	0.0000	0.0000	381188.4000	-13600561.0000	-19386160.0000	188572722.6846
116	188572722.6846	0.9000	581624.4000	431495.1999	2.9702	0.0000	0.0000	419307.2000	-14967861.0000	-21149360.0000	209722082.6846
117	209722082.6846	0.9000	639124.8000	475955.1999	2.9702	0.0000	0.0000	461037.2000	-16427561.0000	-23020160.0000	232742242.6846
118	232742242.6846	0.9000	702224.4000	524935.1999	2.9702	0.0000	0.0000	506744.8000	-17982661.0000	-25000560.0000	257742802.6846
119	257742802.6846	0.9000	771436.8000	578899.1999	2.9702	0.0000	0.0000	557000.8000	-19636161.0000	-27093560.0000	284836362.6846
120	284836362.6846	0.9000	847319.2000	638355.1999	2.9702	0.0000	0.0000	612000.8000	-21391061.0000	-29302160.0000	314138522.6846
121	314138522.6846	0.9000	930472.8000	703859.1999	2.9702	0.0000	0.0000	672000.8000	-23250361.0000	-31629360.0000	345767882.6846
122	345767882.6846	0.9000	1021552.8000	776019.1999	2.9702	0.0000	0.0000	737000.8000	-25217061.0000	-34078160.0000	379846042.6846
123	379846042.6846	0.9000	1121272.8000	855499.1999	2.9702	0.0000	0.0000	808000.8000	-27294161.0000	-36651560.0000	416497602.6846
124	416497602.6846	0.9000	1230408.0000	943019.1999	2.9702	0.0000	0.0000	885000.8000	-29484661.0000	-39352560.0000	455850162.6846
125	455850162.6846	0.9000	1349800.8000	1039359.1999	2.9702	0.0000	0.0000	969000.8000	-31791561.0000	-42184160.0000	498034322.6846
126	498034322.6846	0.9000	1480361.2000	1145379.1999	2.9702	0.0000	0.0000	1061000.8000	-34217861.0000	-45149360.0000	543183682.6846
127	543183682.6846	0.9000	1623077.2000	1262019.1999	2.9702	0.0000	0.0000	1162000.8000	-36766561.0000	-48251160.0000	591434842.6846
128	591434842.6846	0.9000	1779020.4000	1390315.1999	2.9702	0.0000	0.0000	1273000.8000	-39440661.0000	-51492560.0000	642927402.6846
129	642927402.6846	0.9000	1949353.2000	1531395.1999	2.9702	0.0000	0.0000	1395000.8000	-42243161.0000	-54876560.0000	697803962.6846
130	697803962.6846	0.9000	2135336.4000	1686483.1999	2.9702	0.0000	0.0000	1529000.8000	-45177061.0000	-58406160.0000	756210122.6846
131	756210122.6846	0.9000	2338336.8000	1856899.1999	2.9702	0.0000	0.0000	1676000.8000	-48245361.0000	-62084360.0000	818294482.6846
132	818294482.6846	0.9000	2559827.2000	2044059.1999	2.9702	0.0000	0.0000	1837000.8000	-51451061.0000	-65914160.0000	884208642.6846
133	884208642.6846	0.9000	2801395.2000	2249475.1999	2.9702	0.0000	0.0000	2013000.8000	-54797161.0000	-69898560.0000	954107202.6846
134	954107202.6846	0.9000	3064744.8000	2474763.1999	2.9702	0.0000	0.0000	2206000.8000	-58286661.0000	-74040560.0000	1028147762.6846
135	1028147762.6846	0.9000	3351701.2000	2721643.1999	2.9702	0.0000	0.0000	2417000.8000	-61922561.0000	-78343160.0000	1106490922.6846
136	1106490922.6846	0.9000	3664219.2000	2992963.1999	2.9702	0.0000	0.0000	2647000.8000	-65707861.0000	-82809360.0000	1189300282.6846
137	1189300282.6846	0.9000	4004396.4000	3291703.1999	2.9702	0.0000	0.0000	2898000.8000	-69645561.0000	-87442160.0000	1276742442.6846
138	1276742442.6846	0.9000	4374480.8000	3620983.1999	2.9702	0.0000	0.0000	3172000.8000	-73738661.0000	-92244560.0000	1368987002.6846
139	1368987002.6846	0.9000	4776876.4000	3984107.1999	2.9702	0.0000	0.0000	3470000.8000	-77990161.0000	-97219560.0000	1466206562.6846
140	1466206562.6846	0.9000	5214160.8000	4384571.1999	2.9702	0.0000	0.0000	3795000.8000	-82403061.0000	-102370160.0000	1568576722.6846
141	1568576722.6846	0.9000	5689104.0000	4826083.1999	2.9702	0.0000	0.0000	4150000.8000	-86980361.0000	-107699360.0000	1676276082.6846
142	1676276082.6846	0.9000	6204687.6000	5312563.1999	2.9702	0.0000	0.0000	4537000.8000	-91725061.0000	-113210160.0000	1789486242.6846
143	1789486242.6846	0.9000	6764124.0000	5847163.1999	2.9702	0.0000	0.0000	4959000.8000	-96640161.0000	-118905560.0000	1908391802.6846
144	1908391802.6846	0.9000	7370880.0000	6433243.1999	2.9702	0.0000	0.0000	5419000.8000	-101727661.0000	-124788560.0000	2033180362.6846
145	2033180362.6846	0.9000	8028696.0000	7074523.1999	2.9702	0.0000	0.0000	5919000.8000	-106989561.0000	-130862160.0000	2164042522.6846
146	2164042522.6846	0.9000	8741616.0000	7775043.1999	2.9702	0.0000	0.0000	6463000.8000	-112427861.0000	-137129360.0000	2301171882.6846
147	2301171882.6846	0.9000	9513984.0000	8539203.1999	2.9702	0.0000	0.0000	7053000.8000	-118044561.0000	-143593160.0000	2444765042.6846
148	2444765042.6846	0.9000	10350480.0000	9371763.1999	2.9702	0.0000	0.0000	7692000.8000	-123841661.0000	-150255560.0000	2595020602.6846
149	2595020602.6846	0.9000	11255136.0000	10277843.1999	2.9702	0.0000	0.0000	8384000.8000	-129821161.0000	-157119560.0000	2752140162.6846
150	2752140162.6846	0.9000	12232344.0000	11262963.1999	2.9702	0.0000	0.0000	9132000.8000	-135985061.0000	-164188160.0000	2916328322.6846
151	2916328322.6846	0.9000	13286856.0000	12332043.1999	2.9702	0.0000	0.0000	9940000.8000	-142335361.0000	-171464360.0000	3087792682.6846
152	3087792682.6846	0.9000	14423784.0000	13490403.1999	2.9702	0.0000	0.0000	10812000.8000	-148874061.0000	-178950160.0000	3266742842.6846
153	3266742842.6846	0.9000	15648600.0000	14743683.1999	2.9702	0.0000	0.0000	11751000.8000	-155603161.0000	-186647560.0000	3453390402.6846
154	3453390402.6846	0.9000	16967136.0000	16097043.1999	2.9702	0.0000	0.0000	12761000.8000	-162524661.0000	-194558560.0000	3647948962.6846
155	3647948962.6846	0.9000	18385592.0000	17555523.1999	2.9702	0.0000	0.0000	13846000.8000	-169640561.0000	-202685160.0000	3850634122.6846
156	3850634122.6846	0.9000	19910568.0000	19125603.1999	2.9702	0.0000	0.0000	15010000.8000	-176952861.0000	-211029360.0000	4061663482.6846
157	4061663482.6846	0.9000	21549072.0000	20814963.1999	2.9702	0.0000	0.0000	16257000.8000	-184463561.0000	-219593160.0000	4281256642.6846
158	4281256642.6846	0.9000	23309520.0000	22630323.1999	2.9702	0.0000	0.0000	17592000.8000	-192173661.0000	-228378560.0000	4509635202.6846
159	4509635202.6846	0.9000	25199760.0000	24581523.1999	2.9702	0.0000	0.0000	19019000.8000	-200085161.0000	-237387560.0000	4747022762.6846
160	4747022762.6846	0.9000	27228048.0000	26675763.1999	2.9702	0.0000	0.0000	20543000.8000	-208200061.0000	-246622160.0000	4993645322.6846
161	4993645322.6846	0.9000	29403984.0000	28918803.1999	2.9702	0.0000	0.0000	22169000.8000	-216520361.0000	-256084360.0000	5249729682.6846
162	5249729682.6846	0.9000	31737504.0000	31324083.1999	2.9702	0.0000	0.0000	23901000.8000	-225048061.0000	-265776160.0000	5515505842.6846
163	5515505842.6846	0.9000	34239888.0000	33904563.1999	2.9702	0.0000	0.0000	25744000.8000	-233785161.0000	-275699560.0000	5791205402.6846
164	5791205402.6846	0.9000	36922752.0000	36673203.1999	2.9702	0.0000	0.0000	27703000.8000	-242733661.0000	-285856560.0000	6077061962.6846
165	6077061962.6846	0.9000	39798096.0000	39643443.1999	2.9702	0.0000	0.0000	29783000.8000	-251895561.0000	-296249160.0000	6373311122.6846
166	6373311122.6846	0.9000	42878256.0000	42826803.1999	2.9702	0.0000	0.0000	31989000.8000	-261272861.0000	-306879360.0000	6680190482.6846
167	6680190482.6846	0.9000	46175904.0000	46233363.1999	2.9702	0.0000	0.0000	34326000.8000	-270867561.0000	-317749160.0000	6997940642.6846
168	6997940642.6846	0.9000	49704048.0000	49876083.1999	2.9702	0.0000	0.0000	36799000.8000	-280681661.0000	-328860560.0000	7326801202.6846
169	7326801202.6846	0.9000	53476032.0000	53760963.1999	2.9702	0.0000	0.0000	39414000.8000	-290717161.0000	-340215560.0000	7667016762.6846
170	7667016762.6846	0.9000	57505536.0000	57894963.1999	2.9702	0.0000	0.0000	42176000.8000	-300976061.0000	-351816160.0000	8018832922.6846
171	8018832922.6846	0.9000	61806576.0000	62292963.1999	2.9702	0.0000	0.0000	45091000.8000	-311460361.0000	-363664360.0000	8382497282.6846
172	8382497282.6846	0.9000	66393504.0000	66969363.1999	2.9702	0.0000	0.0000	48164000.8000	-322172061.0000	-375762160.0000

TABLE B-5 (CONTINUED)

	1 CPSTRT	2 DEPREC	3 INTRST	4 COVRGE	5 TXCRDT	6 TAXABL	7 FEDTAX	8 STXABL	9 EQYRTN	10 PROPTX	11 FEDTIN
1	34.8920	0.0000	3.8491	1.1547	0.0000	-3.8491	0.0000	-3.8491	0.0000	0.0000	0.0000
2	154.3647	0.0000	16.9801	5.0940	0.0000	-16.9801	0.0000	-16.9801	0.0000	0.0000	0.0000
3	325.8582	0.0000	35.8444	10.7533	0.0000	-35.8444	0.0000	-35.8444	0.0000	0.0000	0.0000
4	381.5421	14.8514	41.9696	12.5908	0.0000	-56.2322	0.0000	-53.2620	0.0000	2.9702	0.0000
5	422.9229	14.8514	46.5215	13.9564	0.0000	-30.8690	0.0000	-27.8988	0.0000	2.9702	0.0000
6	438.9405	14.8514	48.2834	14.4850	0.0000	-29.9758	0.0000	-27.0056	0.0000	2.9702	0.0000
7	454.0649	14.8514	49.9471	14.9841	0.0000	-28.7987	0.0000	-25.8285	0.0000	2.9702	0.0000
8	468.0122	14.8514	51.4813	15.4443	0.0000	-27.2929	0.0000	-24.3227	0.0000	2.9702	0.0000
9	480.4537	14.8514	52.8499	15.8549	0.0000	-25.4090	0.0000	-22.4388	0.0000	2.9702	0.0000
10	491.0113	14.8514	54.0112	16.2033	0.0000	-23.0900	0.0000	-20.1198	0.0000	2.9702	0.0000
11	499.2499	14.8514	54.9174	16.4752	0.0000	-20.2725	0.0000	-17.3023	0.0000	2.9702	0.0000
12	504.6710	14.8514	55.5138	16.6541	0.0000	-16.8843	0.0000	-13.9141	0.0000	2.9702	0.0000
13	506.7039	14.8514	55.7374	16.7212	0.0000	-12.8444	0.0000	-9.8742	0.0000	2.9702	0.0000
14	504.6969	14.8514	55.5166	16.6549	0.0000	-7.9614	0.0000	-5.0916	0.0000	2.9702	0.0000
15	497.9073	14.8514	54.7698	16.4309	0.0000	-2.4337	0.0000	0.5365	0.0000	2.9702	0.0000
16	485.4896	14.8514	53.4038	16.0211	0.0000	4.1552	0.0000	7.1254	0.0000	2.9702	0.0000
17	466.4830	14.8514	51.3131	15.3939	0.0000	11.8345	0.0000	14.8047	0.0000	2.9702	0.0000
18	439.7971	14.8514	48.3776	14.5132	0.0000	20.7497	0.0000	23.7199	0.0000	2.9702	0.0000
19	404.1960	14.8514	44.4615	13.3384	0.0000	31.0640	0.0000	34.0342	0.0000	2.9702	0.0000
20	358.2806	14.8514	39.4108	11.8232	0.0000	42.9609	0.0000	45.9311	0.0000	2.9702	0.0000
21	300.4683	14.8514	33.0515	9.9154	0.0000	56.6456	0.0000	59.6158	0.0000	2.9702	0.0000
22	229.9713	14.8514	25.1868	7.5560	0.0000	72.3485	0.0000	75.3187	0.0000	2.9702	0.0000
23	141.7714	14.8514	15.5948	4.6784	0.0000	107.0733	0.0000	110.0435	0.0000	2.9702	0.0000

KEY TO CALCULATIONS IS AS FOLLOWS:
COLUMN 1 = TOTAL CAPITAL AT START OF YEAR
COLUMN 2 = DEPRECIATION ALLOWANCE FOR TAXES
COLUMN 3 = INTEREST ON DEBT
COLUMN 4 = INTEREST COVERAGE (30%)
COLUMN 5 = INVESTMENT TAX CREDIT TAKEN THIS YEAR
COLUMN 6 = FEDERAL TAXABLE INCOME
COLUMN 7 = FEDERAL INCOME TAX PAID
COLUMN 8 = STATE TAXABLE INCOME
COLUMN 9 = AFTER-TAX RETURN ON EQUITY
COLUMN 10 = LOCAL PROPERTY TAX PAID
COLUMN 11 = CALCULATED FEDERAL INCOME TAX PRIOR TO NONNEGATIVITY CONSTRAINT

Number/
Numéro

2

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VANCOUVER, CANADA V6E 2E9

A Study on the Feasibility of Underground Coal Gasification in the Bowron and Tulameen Coalfields of British Columbia. (Part of the Cost Shared Canadian Coal Conversion Program.)

Appendix A

GEOLOGICAL CHARACTERISTICS OF THE BOWRON AND TULAMEEN COALFIELDS WITH RESPECT TO UNDERGROUND GASIFICATION

Prepared for British Columbia Hydro & Power Authority, Gas Operations
3777 Lougheed Highway
Vancouver, B.C.
V6B 4T6

February 3, 1983

Author: C.R. Saunders, P. Eng. Vancouver, Canada

Work on this project was conducted under the auspices of the Canada Centre for Mineral and Energy Technology, Energy Mines and Resources Canada.

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SUMMARY

The purpose of this study is to provide data on the characteristics and nature of the Bowron and Tulameen coalfields, and on the quality and reserves of the coal seams in these coalfields. This information is presented mainly in the form of maps and drawings; written descriptions are minimal.

The Tulameen Coalfield contains ample coal, beyond the limits of proposed mining, that is suitable for underground gasification. The coal in the Bowron Coalfield, that can be identified from present exploration data as suitable for underground gasification, is being considered for underground mining by the holders of the coal licences covering the coalfield.

INTRODUCTION

PURPOSE AND OBJECTIVES OF THE STUDY

This study is a follow-up to a previous study done for British Columbia Hydro & Power Authority entitled "Potential Coal Sources in British Columbia Suitable for In Situ Gasification", dated March, 1981. The previous study was included as an appendix in a report by B.H. Levelton & Associates Limited entitled "A Study of the Suitability of British Columbia and Nova Scotia Coal Resources for Underground Gasification", also dated March, 1981.

The B.H. Levelton study concluded that the Bowron River Coalfield is the most suitable coal deposit, and the Tulameen Coalfield the second most suitable coal deposit, for underground gasification in British Columbia. This led to authorization being given for further, more detailed studies of the technical and economic aspects of underground gasification in these two deposits.

This Dolmage Campbell report provides the geological background and resource estimates necessary for the technical and economic investigations that are to be made by B.H. Levelton & Associates Ltd.

Much of the required information is contained in the drawings and consequently written descriptions have been kept to a minimum.

The general coalfield locations are shown on Figure 1.

STUDY PARAMETERS

The following parameters have been employed, with some flexibility, in defining the resources of the two coal deposits:

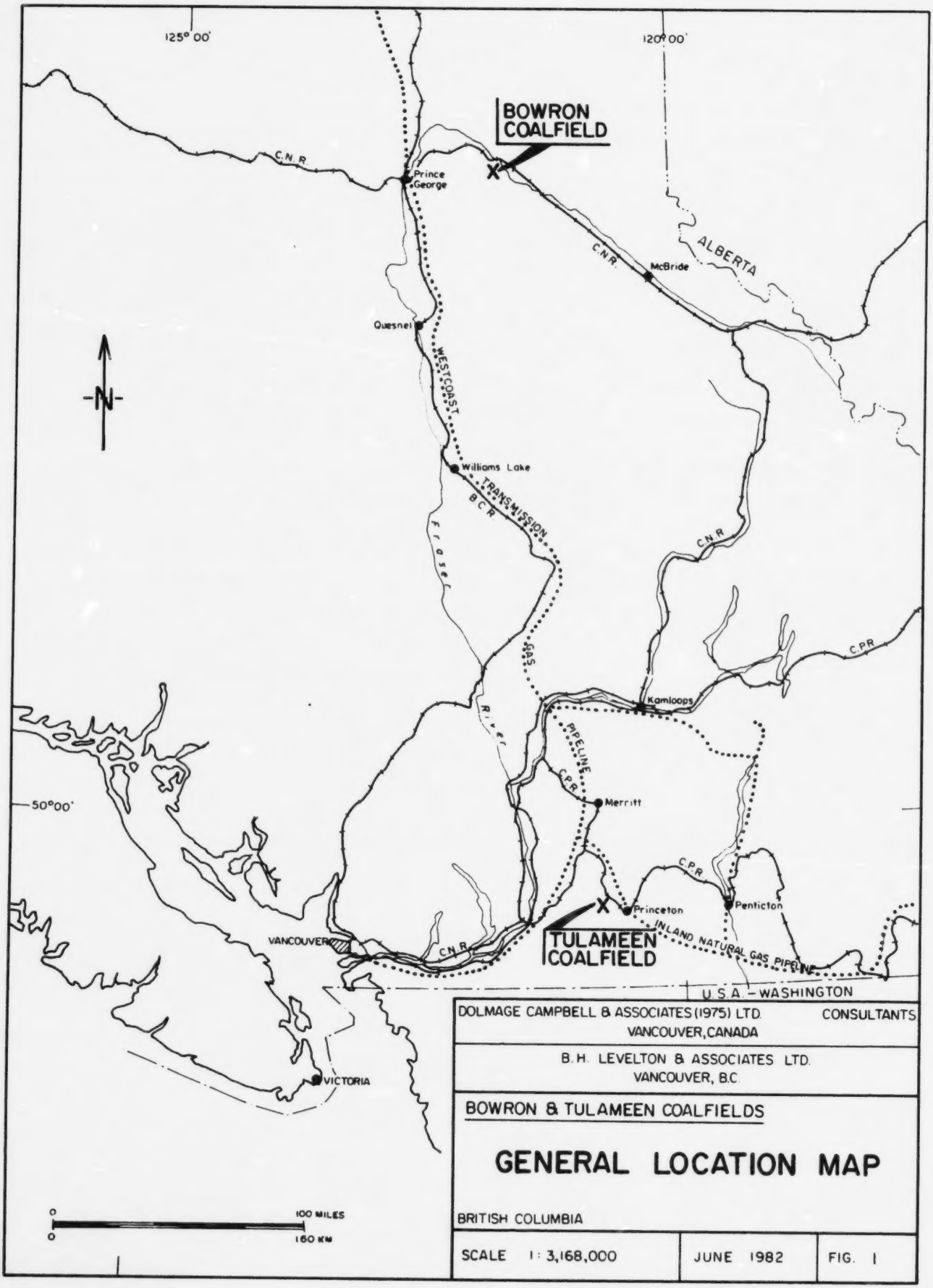
1. Minimum seam thickness considered is one metre.

2. Minimum workable seam depth is 100 metres; resources are estimated for depth increments of 100-300 metres, 300-600 metres, and greater than 600 metres.

3. No resources are included within 100 metres laterally or downdip of old or proposed mine workings.

4. Severely crushed areas in coal zones are excluded where they may result in channelling to mine workings or to surface.

5. Total ash content (inherent ash in the coal plus rock partings) up to approximately 50 percent is acceptable.



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BOWRON & TULAMEEN COALFIELDS

GENERAL LOCATION MAP

BRITISH COLUMBIA

SCALE 1 : 3,168,000	JUNE 1982	FIG. 1

SOURCES OF DATA

General information about the Bowron and Tulameen coalfields has been obtained from Federal and Provincial government publications, articles in technical publications, and previous coal studies done by Dolmage Campbell & Associates Ltd. The detailed data and information about the deposits, including plans for future mining, have been provided by the present owners of the coal licences encompassing the deposits, namely Norco Resources Ltd. (Bowron) and Cyprus Anvil Mining Corporation (Tulameen).

BOWRON

COALFIELD

GENERAL INFORMATION

LOCATION AND PHYSIOGRAPHY

The Bowron Basin is located approximately 55 kilometres east of Prince George, British Columbia in the Bowron River valley. Provincial Highway No. 16 passes to the north of the basin; logging haul roads and access roads are present on both sides of the river in the coalfield area, (Fig. 2).

The Bowron River meanders through a flat-bottomed valley that is two to three kilometres in width and has a mean elevation of 750 metres above sea level. Valley walls rise to summits of about 1220 metres. Overburden consisting of glacial till and river gravels is in the order of 30 metres in thickness. Surface uses comprise logging and cattle grazing. In the coalfield area there is no habitation other than temporary camps.

Climate is typical of the central interior of the province. Summers are warm with occasional temperatures up to 30° Celsius; winters are cold with temperatures remaining below freezing for several months. Precipitation averages 50-75 cm per year.

PROPERTY AND OWNERSHIP

The coal basin, as well as possible extensions to the north and south, is covered by 51 coal licences held by Norco Resources Ltd. of Vancouver, British Columbia, (Fig. 2). The licences encompass an aggregate area in the order of 12,000 hectares. The main portion of the coal basin, as defined by rock exposures, drill holes and magnetic surveys, is approximately 3500 hectares in area.

A list of the coal licences follows:

CL 148
CL 162-163
CL 4458-4464
CL 4723-4727
CL 6043-6044
CL 6343
CL 6540-6572

PROPOSED MINING

Norco Resources Ltd. is proposing to mine some 20 million tonnes of thermal coal by underground methods. The specific areas to be mined and the mining plans have not been finalized. However, the general area in which mining will be done is approximately the same as that for which

reserve areas are shown on Figure 6. Because of data limitations it has been necessary to consider this same area for the study of underground gasification. Coal could be present elsewhere within the basin in quantities and configurations that are suitable for underground gasification but the exploration data in these areas are non-existent or too sparse to confirm such possibilities at this time.

GEOLOGICAL SETTING

REGIONAL GEOLOGY

The basement unit underlying and surrounding the Bowron Basin is the Mississippian age Antler Formation. It consists of pillow basalt, breccia, tuff, minor diorite and gabbro, as well as some chert, argillite and lithic sandstone. It exhibits some metamorphism and weak to moderate deformation.

The Bowron Basin consists of Tertiary clastic sedimentary units. Coarse fractions predominate with much of the stratigraphic section being composed of conglomerate. Other rock types are sandstone, breccia, shale and coal.

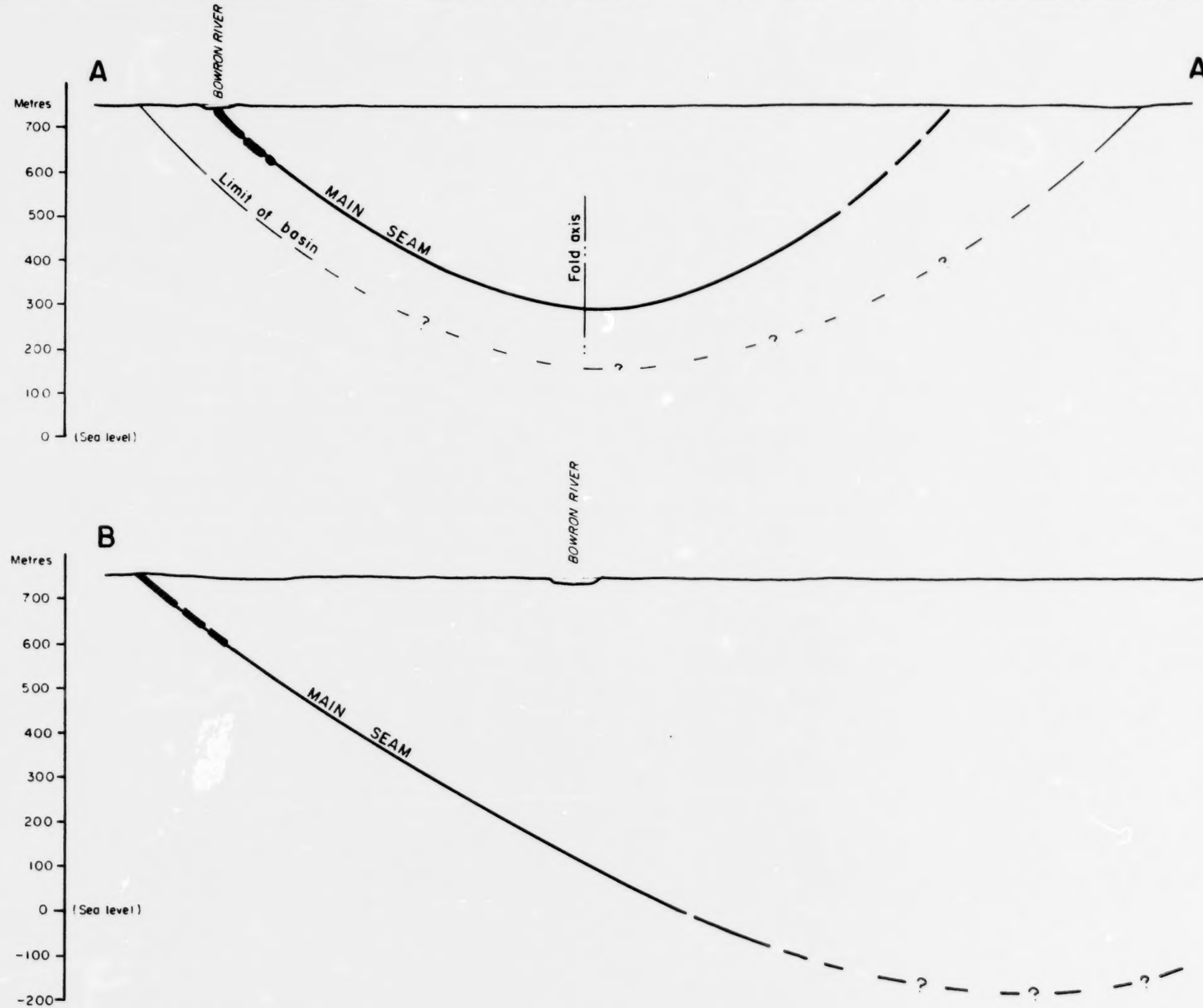
BOWRON COALFIELD

The Bowron Basin, as determined from surface and subsurface geology and from aeromagnetics, consists of a long, narrow northwesterly striking sedimentary basin that is mostly covered by glacial till and river gravels, (Fig. 2). It is synclinal in cross-section and may be bounded by a fault along part of its northeast side, (Fig. 3). At least one transverse fault has been indicated from drilling results within the central portion of the basin.

The explored portion of the basin, the central 25 percent, comprises the Bowron Coalfield.

COAL OCCURRENCES

The Bowron Coalfield contains several coal seams, mostly in the lower part of the stratigraphic section, ranging from a few centimetres to several metres in thickness. Most are discontinuous and of little consequence. However, three are of interest for this study, (Fig. 4). The Lower or 'Main Seam' is the most continuous and the thickest. It appears to be present throughout the explored part of the basin. The two overlying seams, the Middle and the Upper, are reasonably continuous only in the shallower northwestern part of the coalfield. Underground mining is proposed only for the Main Seam.



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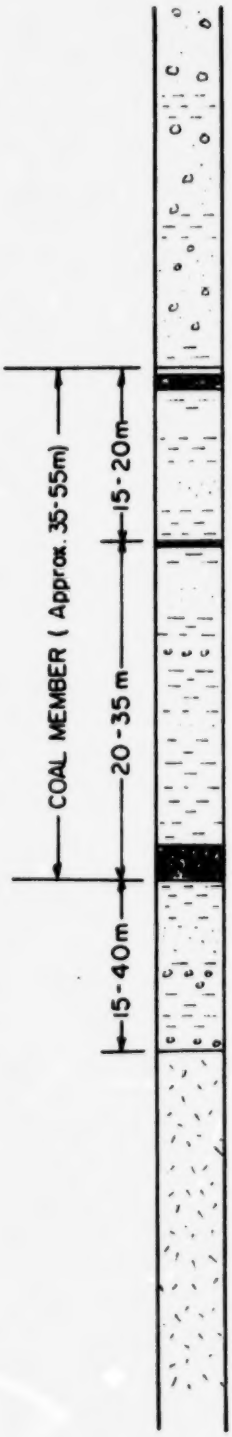
BOWRON COALFIELD

BOWRON COAL DEPOSIT SECTIONS

SCALE 1:10,000	JUNE 1982	FIG. 3



Predominantly conglomerate, sandstone, siltstone and minor shale

Upper seam (1.2 m av.)

Middle seam (1.65m av.)

Shale with some siltstone and minor sandstone and conglomerate; some carbonaceous shale and thin coal seams.

Main seam (5.25m av.)

Unconformity

Basement units (predominantly volcanic rocks)

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BOWRON COALFIELD

STRATIGRAPHIC SECTION COAL MEMBER

SCALE : VERT 1:1000	JUNE 1982	FIG. 4

Shale

0.8 Coal

0.1 Mudstone (or shale)

0.4 Coal

0.3 Coal and mudstone

0.5 Coal

0.3 Siltstone and coaly siltstone

0.5 Coal

0.3 Coal and coaly siltstone

2.0 Coal and high ash coal with mudstone partings

Shale

NOTE: Thickness in metres

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BOWRON COALFIELD

STRATIGRAPHIC SECTION MAIN SEAM

SCALE: VERT 1:100	JUNE 1982	FIG. 5

The Main Seam is overlain and underlain by a variable thickness of shale. Within the seam is clean coal, high ash coal, coaly siltstone and mudstone partings, (Fig. 5). The Middle and Upper seams are also encased in shale or sandy shale, and both probably have similar compositions to the Main Seam.

COAL RESOURCES

QUALITY

The Main Seam of the Bowron River coal deposit has been analyzed sufficiently to provide reliable quality data. The coal seam has the following characteristics (as received basis):

Moisture	4.4%
Volatile Matter	32.9%
Fixed Carbon	41.8%
Ash	21.8 - 45.4%
Sulphur	0.9%
Gross Calorific Value	23.6 MJ/kg (10,130 Btu/lb)
Free Swelling Index	1-3
Rank	High Volatile B Bituminous

The cleaned coal has an inherent ash content of approximately nine percent and a calorific value of 28.7 MJ/kg (12,360 Btu/lb). Thus the aggregate weight percent of partings and high ash coal (greater than 50 percent ash) is approximately 25 percent; the volume percent of the partings and high ash coal (taking into account specific gravities of 1.45 for coal and 2.5 for shale) is approximately 15 percent.

Quality of the Upper and Middle seams has not been determined. For the present they can be assumed to have similar characteristics to the Main Seam.

RESERVES

Total seam reserves (rather than cleaned coal reserves) have been calculated for the Main Seam throughout the coalfield. For the Upper and Middle seams they have been estimated for the northwestern part of the coalfield only. The reserves are calculated from available data along the southwest part of the coalfields and then extrapolated to the northeast. Average thicknesses have been used for each seam: 5.25 metres for the Main Seam, 1.65 metres for the Middle Seam, and 1.2 metres for the Upper Seam. Aggregate cleaned coal thicknesses would be, respectively, 4.45 metres, 1.4 metres and 1.0 metres. The reserve areas are shown on Figure 6 and the tonnages in Table I.

TABLE I

BOWRON COALFIELD - RESERVES

	AREA	MAIN SEAM	MIDDLE SEAM	UPPER SEAM	ALL SEAMS
		(Metric tonnes x 10^6)			
A	100-300 m, <15°	1.7	0.4	0.3	2.4
B	100-300 m, 15°-30°	0.4	0.1	0.1	0.6
C	100-300 m, 15°-30°	3.1	0.8	0.5	4.4
		3.5	0.9	0.6	5.0
D	100-300 m, >30°	2.2	0.5	0.3	3.0
E	100-300 m, >30°	2.3	0.5	0.3	3.1
F	100-300 m, >30°	4.3	-	-	4.3
		8.8	1.0	0.6	10.4
G	300-600 m, <15°	4.8	1.5	1.1	7.4
H	300-600 m, 15°-30°	0.9	0.3	0.2	1.4
I	300-600 m, 15°-30°	1.8	0.6	0.4	2.8
J	300-600 m, 15°-30°	4.1	-	-	4.1
		6.8	0.9	0.6	8.3
K	300-600 m, >30°	0.4	0.1	0.1	0.6
L	300-600 m, >30°	0.2	0.1	0.1	0.4
M	300-600 m, >30°	0.1	-	-	0.1
N	300-600 m, >30°	5.3	-	-	5.3
		6.0	0.2	0.2	6.4
O	>600 m, 15°-30°	13.8	-	-	13.8
P	>600 m, >30°	5.2	-	-	5.2
	TOTALS	50.6	4.9	3.4	58.9
	100-300 m	14.0	2.3	1.5	17.8
	300-600 m	17.6	2.6	1.9	22.1
	>600 m	19.0	-	-	19.0
	<15°	6.5	1.9	1.4	9.8
	15°-30°	24.1	1.8	1.2	27.1
	>30°	20.0	1.2	0.8	22.0

TULAMEEN

COALFIELD

GENERAL INFORMATION

LOCATION AND PHYSIOGRAPHY

The Tulameen Basin is located four kilometres south of the small community of Tulameen, three kilometres west of the equally small community of Coalmont, and 15 kilometres west of the city of Princeton in southern British Columbia. A paved secondary road connects Tulameen and Coalmont with Princeton along the Tulameen River valley. Gravel roads provide access from Coalmont up to the plateau on which the Tulameen Basin rests.

The Basin has moderate relief with elevations ranging from 1100 to 1450 metres. Creeks are sparse. Overburden cover is variable but probably averages less than ten metres. Surface use is primarily for cattle grazing.

Climate is southern interior dry belt. Summers are quite warm with temperatures up to 35° Celsius. Winters are cold, particularly at higher elevations. Precipitation averages less than 40 centimetres per year.

PROPERTY AND OWNERSHIP

The coal basin is covered by 15 coal licences with a total area of approximately 2500 hectares, (Fig. 7). Cyprus Anvil Mining Corporation is the recorded holder of all the licences. The licence numbers are:

CL 69-71
CL 125-126
CL 145-147
CL 153-154
CL 158-159
CL 3663-3665

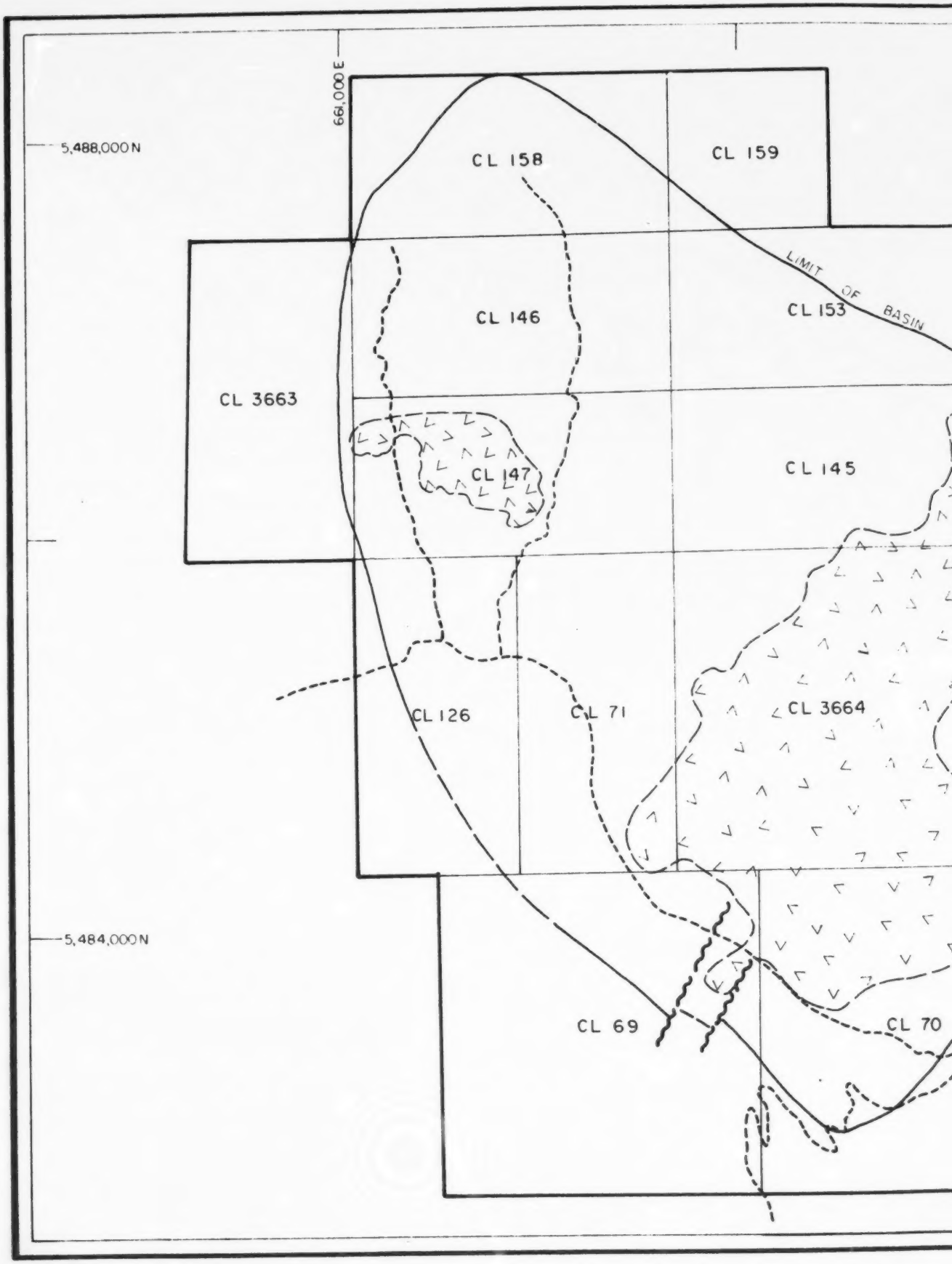
PROPOSED MINING

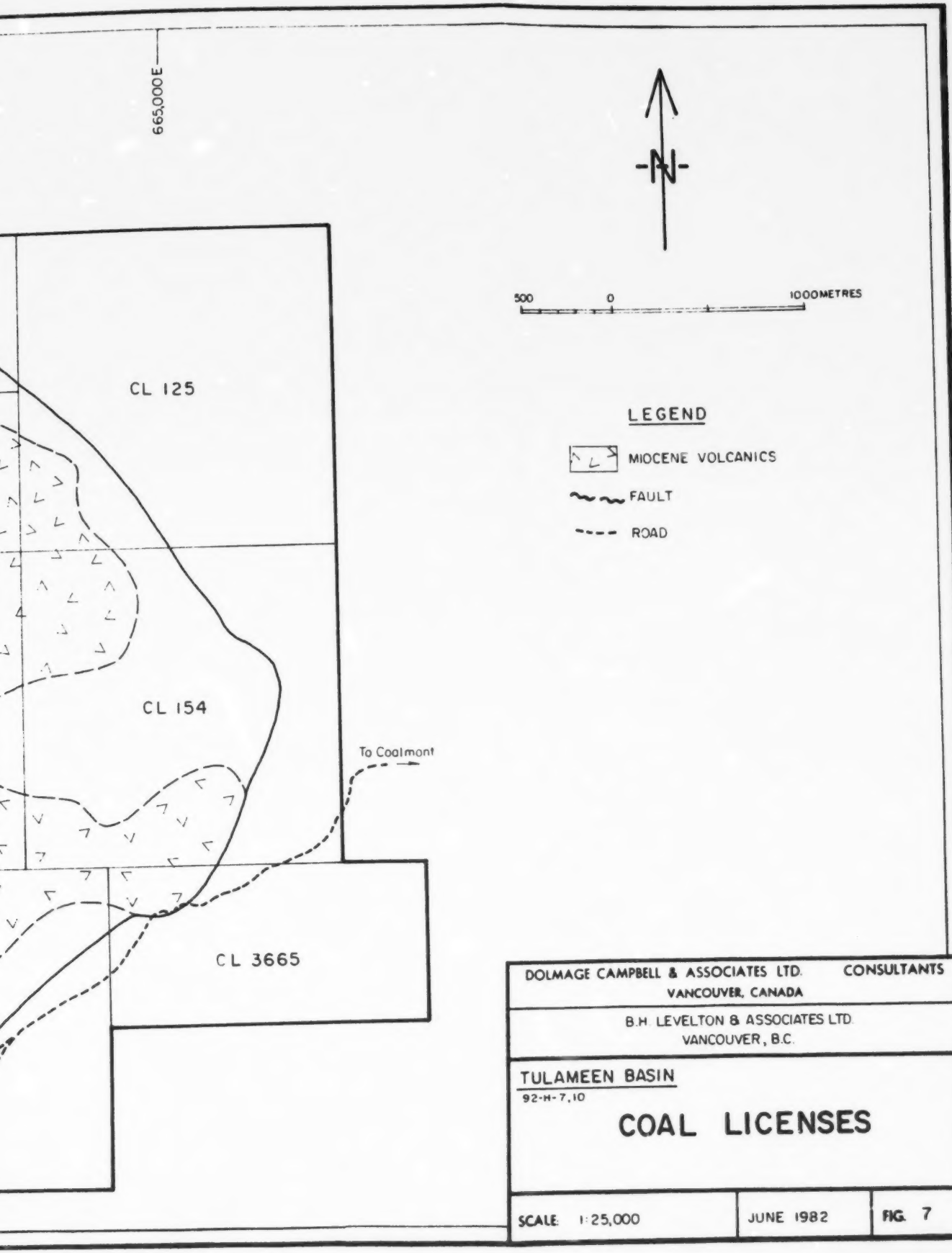
Cyprus Anvil Mining Corporation plans to mine the Main coal seam on the west side of the basin by open pit methods. They have completed feasibility studies that show the locations of the open pit and other surface features, (Fig. 8). Initiation of mining is dependent upon thermal coal prices and a sales contract.

GEOLOGICAL SETTING

REGIONAL GEOLOGY

The Tulameen Basin consists of an oval shaped, synclinally folded sequence of Tertiary sedimentary and volcanic rocks which lie unconform-


66,000 E
5,488,000 N
5,484,000 N
CL 158
CL 159
CL 146
CL 153
LIMIT OF BASIN
CL 3663
CL 147
CL 145
CL 126
CL 71
CL 3664
CL 69
CL 70



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TULAMEEN BASIN
92-H-7,10

COAL LICENSES

SCALE: 1:25,000 | JUNE 1982 | FIG. 7

ably on a basement of Upper Triassic Nicola Group metamorphosed volcanic and sedimentary units. Younger Tertiary basalts cap portions of the sedimentary rocks, (Fig. 9). The sedimentary units comprise the Tulameen Coalfield.

TULAMEEN COALFIELD

The Tulameen Coalfield has been explored by geological mapping, diamond drilling and underground mining. The geological characteristics of the western and southwestern sides of the coalfield are particularly well documented; the central and eastern portions are less well known.

The stratigraphic sequence consists of 580 metres of conglomerate and sandstone overlying 130 metres of coal measure which in turn overlies a 60 metre basal member consisting of sandstone, shale and siltstone. The coal measure is composed of shale, siltstone, sandy shale and minor sandstone with interbedded coal and bentonite, (Fig. 11).

The sedimentary units are folded into a somewhat elongate dish-shaped basin oriented in a northwest-southeast direction. Depth to the centre of the basin is in excess of 600 metres. Faulting has been identified in the southern part of the coalfield, (Figs. 8, 9, 10).

COAL OCCURRENCES

The Tulameen Coalfield contains two seams of interest for possible underground gasification - the 'Main' and the 'Lower'. The Main Seam has been well explored, tested and mined whereas little is known about the Lower Seam other than that it is "dirty" and averages 3.5 metres in thickness. The Main Seam appears to be continuous throughout the basin although it has never been tested at depth. It has an average thickness of about 17.5 metres. Some crushing of the coal has been reported from old workings on the northwest side of the coalfield. This is thought to be a near-surface feature.

The Main Seam consists of sections of clean coal, dirty coal, mudstone and bentonite, (Fig. 12).

COAL RESOURCES

QUALITY

Quality data are available for the Main Seam of the Tulameen Coalfield but not for the Lower Seam. However, it can be assumed that Lower Seam quality is similar to that of the Main Seam except that the ash content is higher.

661,000E

665,000E

5,488,000N

5,484,000N

FAULT ZONE

-N-

500 0 1000METRES

LEGEND

- VOLCANICS - fine grained basalt
- SANDSTONE - granule conglomerate, coarse sandstone, minor mudstone, shale, thin coal
- COAL MEMBER - mudstone, shale, coal, bentonite
- SANDSTONE - coarse to fine, some mudstone & shale
- VOLCANICS - fragmental, andesitic to felsic
- VOLCANICS & SEDIMENTS - metamorphosed
- MAIN COAL SEAM
- FAULT

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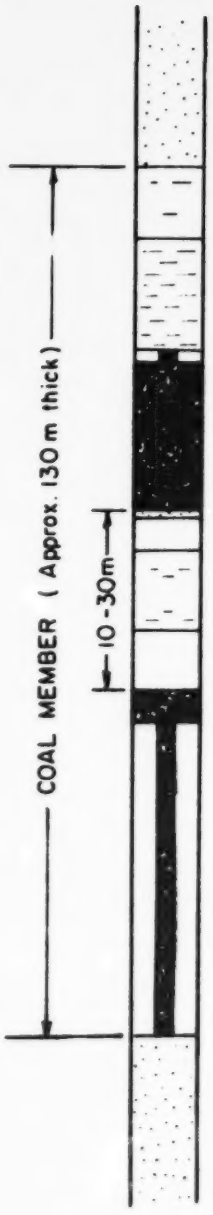
TULAMEEN COALFIELD
92H-7,10

GENERAL GEOLOGY

SCALE 1:25,000	JUNE 1982	FIG 9



Upper sandstone (600 metres thick)

Mudstone and shale, blocky breaking

Fissile shale, thinly laminated

Bentonite, thin dirty coal and mudstone

Main coal zone

Sandstone, light grey, medium grained, muddy matrix
Mudstone, dark grey, massive and blocky

Interbedded shale, mudstone, sandy mudstone, distinctive light to dark grey colour banding

Mudstone, massive to medium laminated

Lower coal zone

Interbedded fragmental bentonitic tuff, thin coal seams, and coaly bentonitic mudstone

Lower sandstone (100 - 150 metres thick)

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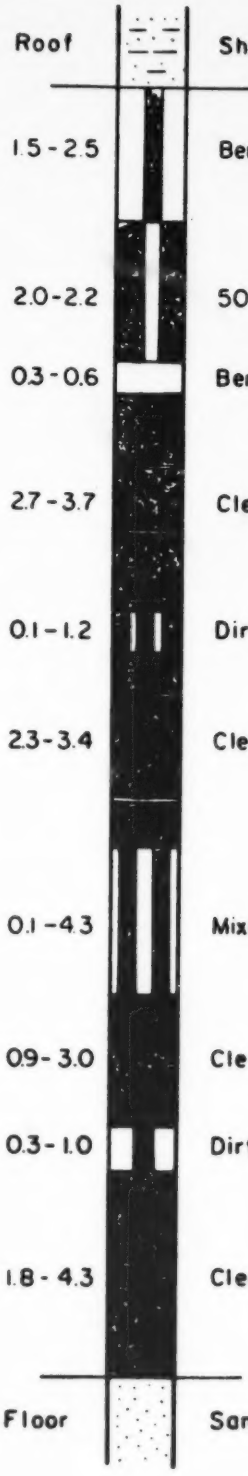
TULAMEEN COALFIELD

STRATIGRAPHIC SECTION
COAL MEMBER

SCALE : VERT 1 1000	JUNE 1982	FIG. 11



Roof	Shale and sandstone (10-20m ?)
1.5 - 2.5	Bentonite; some thin dirty coal and mudstone
2.0-2.2	50-95% clean coal ; dirty coal, minor bentonite
0.3 - 0.6	Bentonite
2.7 - 3.7	Clean coal ; local mudstone partings
0.1 - 1.2	Dirty coal
2.3 - 3.4	Clean coal ; local thin bentonite or dirty coal partings
0.1 - 4.3	Mixed dirty coal , clean coal (0 - 75%), mudstone
0.9 - 3.0	Clean coal
0.3 - 1.0	Dirty coal , mudstone
1.8 - 4.3	Clean coal
Floor	Sandstone

NOTE : Thickness in metres

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TULAMEEN COALFIELD

STRATIGRAPHIC SECTION MAIN SEAM

SCALE VERT 1:100	JUNE 1982	FIG. 12

The Main Seam coal has the following characteristics (as received, cleaned coal basis):

Moisture	13.2%
Volatile Matter	27.0%
Fixed Carbon	43.2%
Ash	16.6%
Sulphur	0.6%
Gross Calorific Value	22.09 MJ/kg (9500 Btu/lb)
Free Swelling Index	1-2
Rank	High Volatile C Bituminous

The in situ coal has a much higher ash content than the cleaned coal due to shale partings and high ash coal bands (greater than 50 percent ash). Its ash content is approximately 37 percent at 8 percent moisture (40.9 percent on a dry coal basis). The volume represented by the partings and high ash coal bands is approximately 12 percent of the aggregate seam volume, or about two metres of the total seam thickness of 17.5 metres.

RESERVES

Reserves have been calculated only for the Main Seam because the continuity of the Lower Seam is untested. On the basis of average thickness the Lower Seam would contain about 20 percent of the tonnage of the Main Seam.

Reserves have been calculated for all areas within the coalfield where the Main Seam is greater than 100 metres below surface and 100 metres laterally or down-dip from mine openings and potentially crushed zones. In the central, deeper part of the coalfield the configuration and continuity of the seam are somewhat conjectural because of a lack of exploration data. The reserve areas are shown on Figure 13 and the tonnages in Table II.

TABLE II

TULAMEEN COALFIELD - RESERVES

AREA	TONNAGE ($\times 10^6$)
100-300 m, >30° (1)	22
100-300 m, >30° (2)	5
	27
300-600 m, 15°-30° (5)	23
300-600 m, 15°-30° (6)	17
	40
300-600 m, >30° (3)	39
300-600 m, >30° (4)	12
	51
>600 m, <15° (11)	20
>600 m, <15° (12)	17
	37
>600 m, 15°-30° (8)	55
>600 m, 15°-30° (9)	4
>600 m, 15°-30° (10)	3
	62
>600 m, >30° (7)	8
TOTAL	225
100-300 m	27
300-600 m	91
>600 m	107
<15°	37
15°-30°	102
>30°	86

CONCLUSIONS

Ample coal reserves, some of which are suitable for underground gasification, are present in the Tulameen Coalfield in areas beyond any planned mining.

At the present time, the only coal reserves that can be considered for underground gasification in the Bowron Coalfield are also being considered for underground mining by the present holders of the coal licences. Further exploration might reveal coal elsewhere in the Bowron Basin that could be suitable for the purposes of this study.

122° 00' W

53° 55' N

CL 6572

CL 6571

CL6569

CL 6570

CL 6568

CL 6567

CL 6562

PURDEN LAKE

16

CL6566

CL 6561

CL 6559

BOWRON BASIN

CL 6560

CL 6558

CL 6343

CL 4727

Saw Creek

Nizzo Creek

Kennedy Creek

CL 6565

CL4726

CL6043

CL 6044

Taspai Creek

CL 148

CL 162

CL 4463

CL4461

CL 6564

CL 6563

CL 163

CL 4462

CL 4460

CL 6555

CL 6554

122°00'W

121°45'W

572

CL 6571

CL6569

CL 6570

CL 6562

CL 6567

CL 6568

PURDEN LAKE

18

CL 6566

CL 6561

CL 6559

BOWRON BASIN

CL 6560

CL 6343

CL 6558

CL 4727

Saw Creek

Nitro Creek

Kennedy Creek

CL6565

CL4726

CL6043

CL 6044

Taspai Creek

CL6564

CL 6563

CL 148

CL 162

CL 4463

CL4461

CL 6555

CL 163

CL 4462

CL 4460

CL 6554

A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
A'
B'
300m depth
Old mine workings
Old mine working
LIMIT OF BASEMENT SUBCROP
LIMIT OF
MAIN SE

A

B

C

D

E

F

G

H

I

J

K

L

M

A'

B'

LIMIT OF BASEMENT SUBCROP

Old mine workings

Old mine working

LIMIT

MAIN

300m depth

150

300

500

200

BOWRON BASIN

CL 6560

CL 6558

CL 6343

CL 4727

CL4726

CL6043

CL 6044

CL 148

CL 162

CL 4463

CL4461

CL 163

CL 4462

CL 4460

CL 6557

CL 4464

CL 4459

CL 4458

FIG. 6

CL 6553

CL 6556

CL 4725

CL 4724

CL 6552

CL 4723

CL 6565

CL 6564

CL 6563

CL 6555

CL 6554

CL 6551

CL 6548

CL 6550

CL 6549

CL 65

Saw Creek

Nitro Creek

Kenneth Creek

Taspot Creek

Swamp Creek

Isus Creek

BOWRON RIVER

53°45'N

BOWRON BASIN

CL 6560

CL 6558

CL 6343

CL 4727

Saw Creek

Nizzo Creek

Kenneth Creek

CL 6565

CL4726

CL6043

CL 6044

Taspai Creek

CL 6564

CL 6563

CL 148

CL 162

CL 4463

CL4461

CL 163

CL 4462

CL 4460

CL 6555

CL 6554

CL 6557

CL4464

CL 4459

CL 4458

FIG. 6

CL 6553

CL 4725

CL 4724

CL 4723

CL 6556

CL 6552

Swamp Creek

BOWRON RIVER

Tsus Creek

CL 6551

CL 6548

CL 6550

CL 6549

CL 6547

G

H

K

E

I

Old mine workings

L

M

Old mine working

J

O

F

N

P

A

A'

B

B'

LIMIT OF BASEMENT SUBCROP

MAIN SEAM SUBCROP

LIMIT OF BASEMENT SUBCROP

600m depth

30°

15°

50

100

200

300

400

500

700

E

I

K

L

M

O

J

F

N

P

Old mine workings

Old mine working

A

B

BASEMENT SUBCROP

MAIN SEAM SUBCROP

LIMIT OF BASEMENT SUBCROP

600m depth

30°

300

100

200

0

-100

-200

-300

-400

-500

-600

-700

53°45'N

Swamp

Tsus Creek

CL 6551

CL 6548

CL 6550

CL 6549

CL 6547

CL 6546

CL 6545

CL 6544

CL 6543

CL 6542

CL 6541

CL 6540

LEGEND

UPPER CRETACEOUS OR PALEOCENE

BOWRON RIVER COAL MEASURES ; conglomerate, breccia, sandstone, shale, coal

MISSISSIPPIAN

ANTLER FORMATION ; pillow basalt, breccia, tuff, minor diorite and gabbro ; chert, argillite, lithic sandstone

FAULT

CL 6550 COAL LICENSE

(16) PAVED ROAD

GRAVEL ROAD

N

0 1 2 3 4 KM.

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BOWRON COALFIELD

COAL LICENSES AND GENERAL GEOLOGY

SCALE 1:50,000

JUNE 1982

Swamp

Creek

Tsus

CL 6551

CL 6548

CL 6550

CL 6549

CL 6547

CL 6546

CL 6545

CL 6544

CL 6543

CL 6542

CL 6541

CL 6540

LEGEND

UPPER CRETACEOUS OR PALEOCENE

BOWRON RIVER COAL MEASURES ; conglomerate, breccia, sandstone, shale, coal

MISSISSIPPIAN

ANTLER FORMATION ; pillow basalt, breccia, tuff, minor diorite and gabbro ; chert, argillite, lithic sandstone

FAULT

CL 6550 COAL LICENSE

(16) PAVED ROAD

GRAVEL ROAD

N

1 2 3 4 KM.

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BOWRON COALFIELD

COAL LICENSES AND GENERAL GEOLOGY

SCALE 1:50,000	JUNE 1982	FIG. 2

B

CROP

F

N

P

700

BOWRON RIVER

0 200 400 600 800 METRES

COAL LICENSE BOUNDARY

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BOWRON COALFIELD

STRUCTURAL CONTO
(TOP - MAIN SEAM

SCALE 1:10,000

JUNE 1982

COAL LICENSE BOUNDARY

200 400 600 800 METRES

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BOWRON COALFIELD

STRUCTURAL CONTOURS
(TOP - MAIN SEAM)

SCALE 1:10,000	JUNE 1982	FIG. 6

661,000E

663,000E

5,488,000 N

LIMIT OF BASIN

SURFACE TRACE OF MAIN COAL SEAM

WASTE DUMP

VOLCANIC CAP

ROAD

Collins Gulch

950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450

663,000 E

665,000 E

TRUE NORTH

GRID NORTH 1.43°

950

1000

1050

1100

1150

1200

1250

LIMIT OF BASIN

SURFACE TRACE OF MAIN COAL SEAM

Collins Gulch

Fraser Gulch

A

Elevation
1400m
1200
1000
800
600
400

PROPOSED WASTE DUMP

D-D' SECTION

C-C' SECTION

B-B' SECTION

Volcanic cap

MAIN COAL SEAM

Limit of basin

B

Elevation
1400m
1200
1000

PROPOSED OPEN PIT

PROPOSED WASTE DUMPS

A-A' SECTION

Volcanic cap

B

D-D' SECTION

C-C' SECTION

B-B' SECTION

A'

Elevation

1400 m

1200

1000

800

600

400

Volcanic cap

Volcanic cap

MAIN COAL SEAM

in

B'

A-A' SECTION

Elevation

1400m

1200

1000

661,000E

663,000E

5,488,000 N

A

B'

LIMIT OF BASIN

SURFACE TRACE OF MAIN COAL SEAM

1200

Thinly interbedded coal and volcanics (high ash, >50%)

1

2

3

5

1.5

30

300

663,000E

665,000 E

TRUE NORTH

GRID NORTH 1.43°

LIMIT OF BASIN

B'

SURFACE TRACE OF MAIN COAL SEAM

1200

C'

D'

oal and
50 %)

1

3

300

400

30°

15°

5,486,000 N

5,484,000 N

VOLCANIC CAP

PROPOSED OPEN PIT

TAILING POND

PLANT AREA

U.G. MINE Nº 5

U.G. MINE Nº 4

U.G. MINE Nº 3

WASTE DUMP

MAIN COAL SEAM

VOLCANIC CAP

BLAKEBURN

1200
1250
1300
1350
1400
1450
1500

TAILING POND

PLANT AREA

U.G. MINE Nº 5

U.G. MINE Nº 4

U.G. MINE Nº 3

VOLCANIC CAP

L SEAM

BLAKEBURN

HOLMES CREEK

ROAD TO COALMONT

Fraser

1200
1250
1300
1350
1400
1150
1100
1050
1000
950

1200
1000
800
600
400

Volcanic cap

MAIN COAL SEAM

Limit of basin

A-A' SECTION

C

Elevation

1200m
1000
800
600
400

Volcanic cap

Mined out area

MAIN COAL SEAM

Limit of basin

Volcanic cap

C'

1000

1200

1000

800

600

400

A-A' SECTION

C'

Volcanic cap

Volcanic cap

Elevation

1200m

1000

800

600

400

B

C

D

5,486,000 N

5,484,000 N

PROPOSED OPEN PIT

U.G. MINE Nº 5

U.G. MINE Nº 4

U.G. MINE Nº 3

MAIN COAL SEAM

Possible Fault Zone

Possible Fault Zone

30m depth

300

500

600

700

800

900

1000

1100

1200

1300

3

4

5

7

8

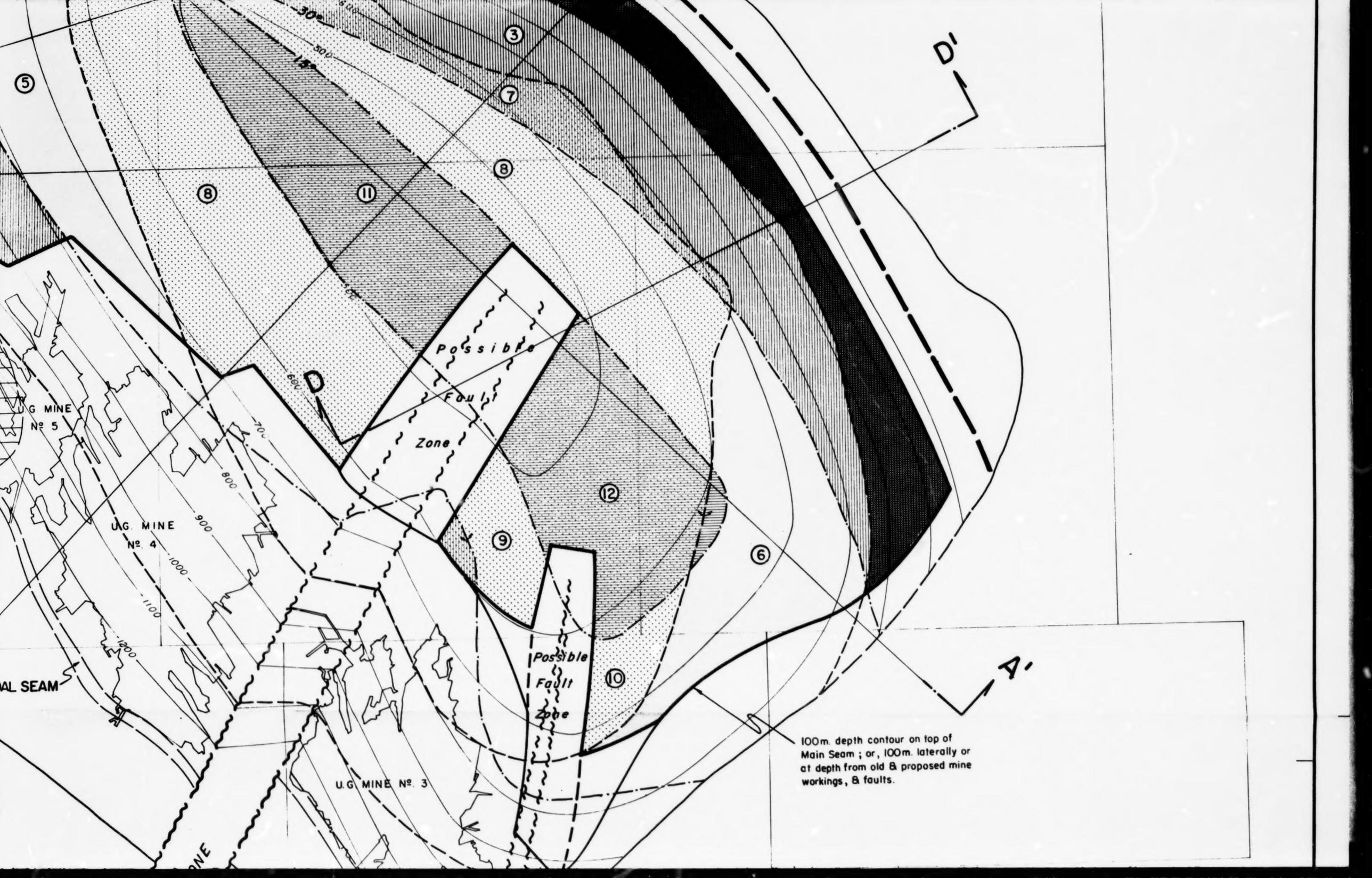
8

11

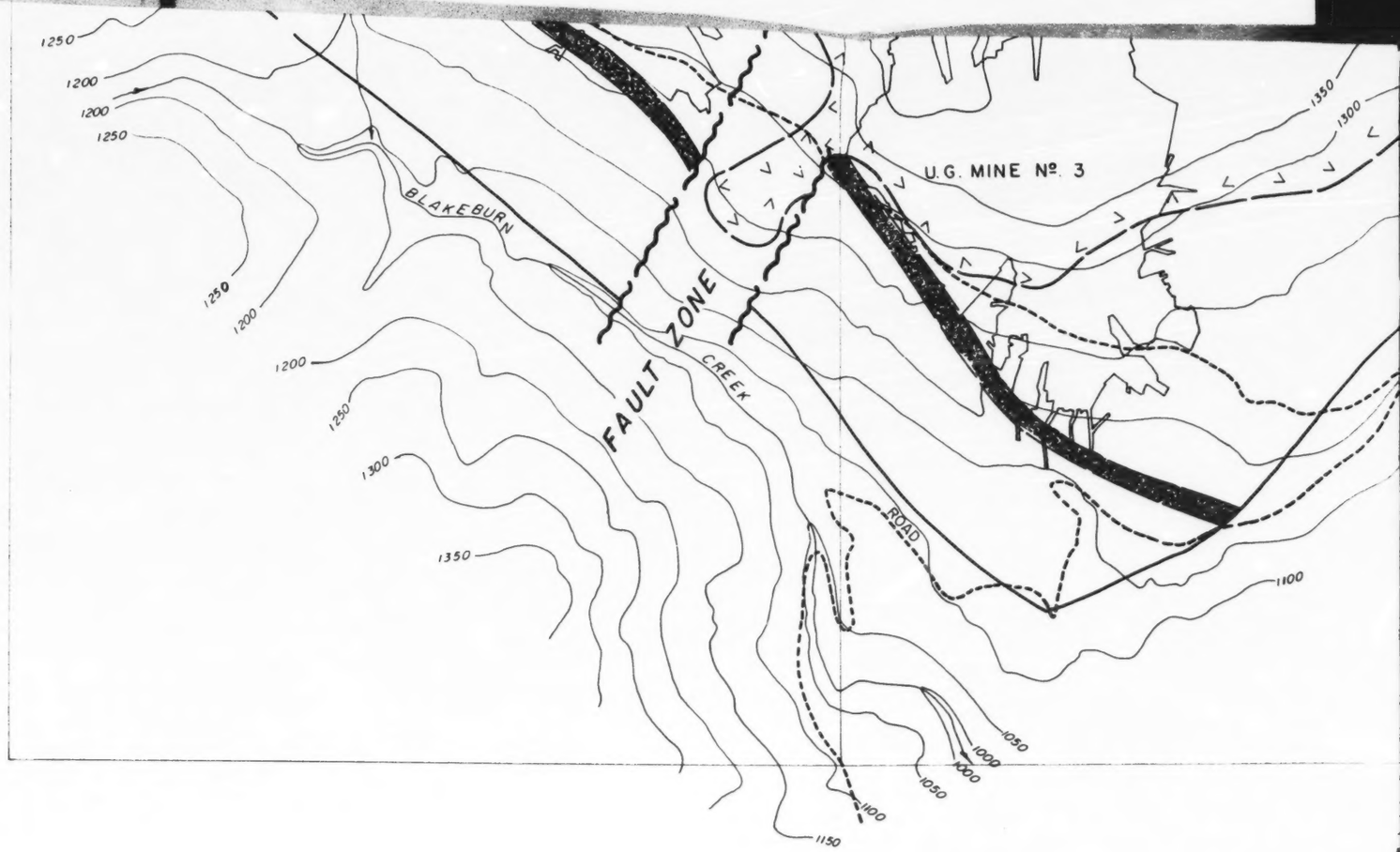
12

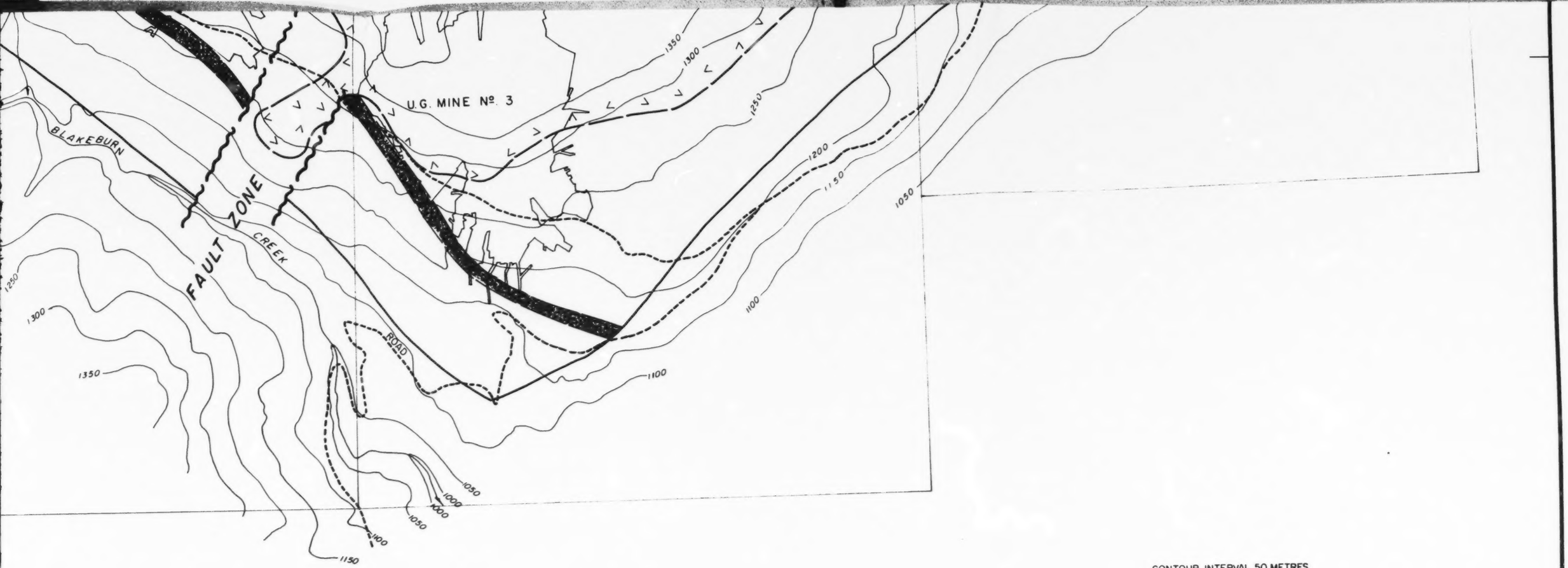
9

10


D
D'
A'
Possible Fault Zone
Possible Fault Zone
U.G. MINE No. 5
U.G. MINE No. 4
U.G. MINE No. 3
AL SEAM
100m. depth contour on top of Main Seam ; or, 100m. laterally or at depth from old & proposed mine workings, & faults.

5,484,000N


1250
1200
1200
1250
1250
1200
1200
1250
1300
1350
BLAKEBURN
FAULT ZONE
CREEK
U.G. MINE Nº. 3
1350
1300
ROAD
1100
1050
1000
1000
1050
1100
1150



CONTOUR INTERVAL 50 METRES

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TULAMEEN COALFIELD

92-H-7,10

COMPILATION MAP

SCALE 1:10,000	JUNE 1982	FIG. 8

400

400

D

A-A' SECTION

Elevation

1200m

1000

800

600

400

Volcanic cap

MAIN COAL SEAM

Limit of basin

? ? ? ? ? ?

400

A-A' SECTION

D'

Elevation

1200 m

1000

800

600

400

Volcanic cap

MAIN COAL SEAM

Limit of basin

FAULT

0 200 400 600 800

METRES

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TULAMEEN COALFIELD

92-H-7,10

TULAMEEN COAL DEPOSIT SECTIONS

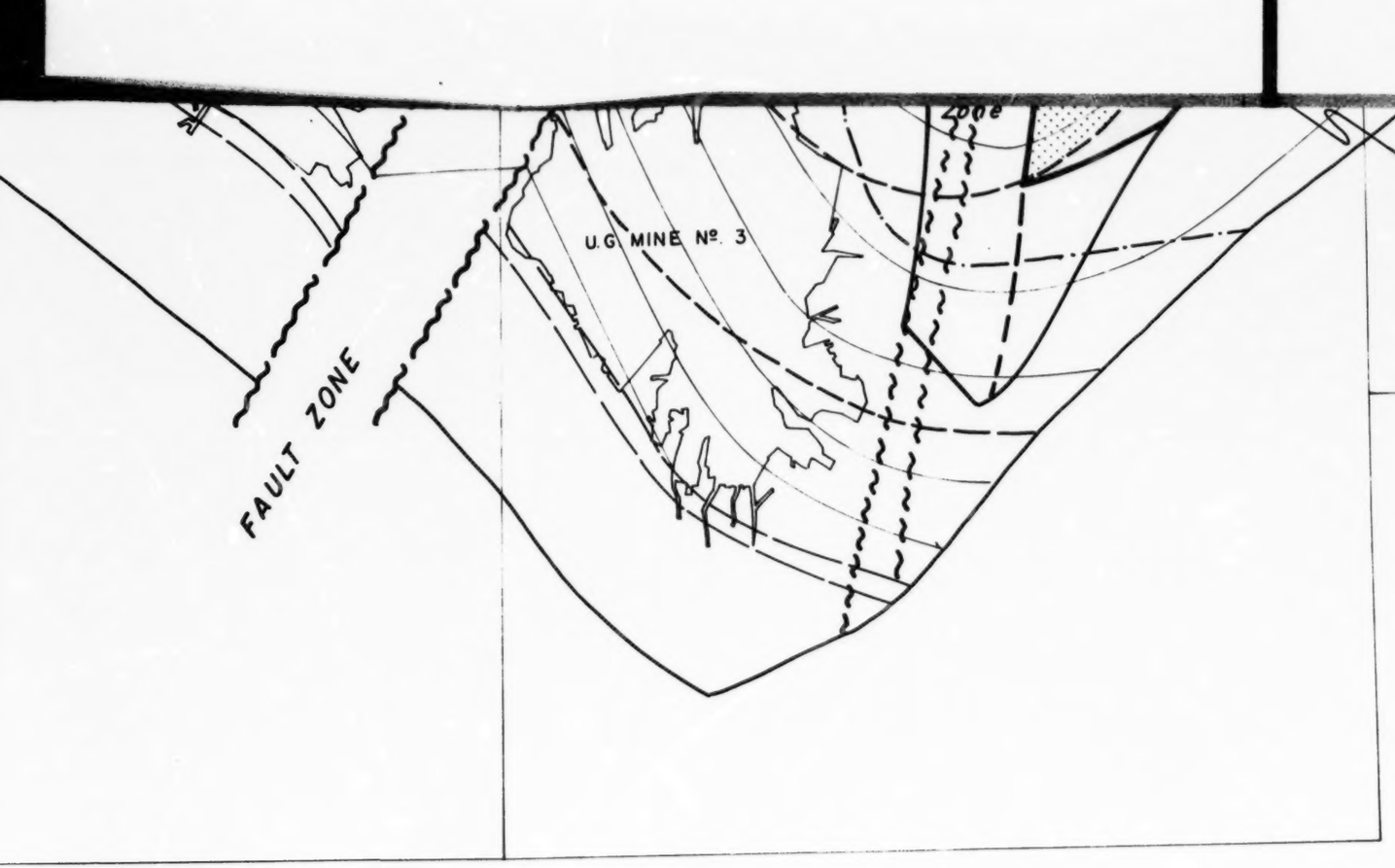
SCALE 1:10,000	JUNE 1982	FIG. 10

5,484,000N

C

U.G. MINE Nº. 3

FAULT ZONE



100m. depth contour on top of Main Seam ; or, 100m. laterally or at depth from old & proposed mine workings, & faults.

0 200 400 600 800
METRES

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TULAMEEN COALFIELD

92-H-7,10

STRUCTURAL CONTOURS (TOP - MAIN SEAM)

SCALE 1:10,000	JUNE 1982	FIG. 13

POOR

QUALITY

ORIGINAL